HUMAN-IN-THE-LOOP EXPERIMENTAL RESEARCH FOR DETECT AND AVOID

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Abstract

This paper provides an overview of a Detect and Avoid (DAA) concept developed by the National Aeronautics and Space Administration (NASA) for integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS), and provides results from human-in-the-loop experiments performed to investigate interoperability and acceptability issues associated with use of the concept with these vehicles and operations. The series of experiments was designed to incrementally assess critical elements of the new concept and the enabling technologies that will be required.

Introduction

The Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) project is a research effort funded by the National Aeronautics and Space Administration (NASA) that spans four NASA research centers. The work described in this paper addresses the development and implementation of concepts and technologies conducted at NASA Langley Research Center, to facilitate public and civil UAS in non-segregated airspace operations. Access to the NAS is hampered by challenges such as the lack of an on-board pilot to see and avoid other aircraft, the lack of protected civil radio frequency spectrum and reliable infrastructure for command and control links, and the wide variation in UAS size, performance (altitudes, speeds, and maneuvering performance) and missions.

The lack of an onboard pilot is clearly the most obvious difference between UAS and traditional aircraft and it is this difference that drives the problem of how to deal with the legal requirement identified in the US Code of Federal Regulations (CFR) and associated International Civil Aviation Organization (ICAO) Annexes that pilots see and avoid other aircraft. To achieve compliance with the "see and avoid" regulatory requirements, a system needs to be developed to assist the UAS pilot to maintain safe separation from other traffic. A Detect and Avoid (DAA, also known as Sense and Avoid or SAA) system is defined as having two functions: a self-separation (SS) function to enable its associated UAS to stay well clear of other aircraft, and a possibly-optional collision avoidance (CA) function to prevent collisions if all other means of separation fail.

This paper provides an overview of the concept of integration for DAA equipped UAS in the NAS and the experimental evaluation plan first introduced in [1], as well as a subset of the research and development work that was completed in the three years following its publication. The focus of the work that ensued was on developing the analytical foundations for the DAA capability, the software implementation for the DAA prototype and the simulation infrastructure needed to conduct the required evaluation activities.

Subsequent sections provide the description and results of two completed human-in-the-loop- (HITL) experiments as well as a brief overview of the objectives and design of an ongoing experiment.

Concept of Integration for UAS Operations in the NAS

The "Concept of Integration for UAS Operations in the NAS", first published in 2012 (also referred to as the NASA DAA concept) [1], has since been the foundation for the research and development activities conducted at NASA Langley Research Center in support the UAS in the NAS project. Furthermore, its overall approach, design elements, and principles have been incorporated by the RTCA Special Committee 228 (SC-228) community as the Concept of Operations (ConOps) for DAA (Detect and Avoid). The concept builds on and extends a foundation of concepts described by the FAA sponsored SAA Workshop Final Report [2] and by various RTCA SC-203 documents [3, 4].

The fundamental design principle of the DAA implementation concept is to enable the smooth integration of DAA equipped UAS into an air traffic services environment by ensuring interoperability with the airspace system, air traffic control (ATC) services, and with existing aircraft equipped with the Traffic Alert & Collision Avoidance System (TCAS).

The concept assumptions are aligned with today's NAS CNS (Communication, Navigation and Surveillance) infrastructure and aimed at minimizing disruption of existing regulations to support the rapid integration of unmanned vehicles in non-segregated airspace. Similarly, it is assumed that an approved and reliable UAS control link capability will be available between unmanned aircraft (UAs) and their respective Ground Control Stations (GCS). It is also assumed that one or more aircraft sensor/tracker capabilities will be available to the UAS, either onboard the UA and/or from ground-based sources, and that these sensor/tracker data will be provided as inputs to sensor fusion and threat detection and/or resolution capabilities. ATC's assumed expectations are that for normal operations, UAS requesting NAS access will be appropriately CNS-equipped and able to comply with the same ATC clearances and instructions as manned aircraft requesting the same services and airspace access.

DAA Functions

As established in [2], a DAA capability comprises two functions: self-separation (SS) and collision avoidance (CA). The SS function is intended as a means of compliance with the regulatory requirements to remain well clear of other aircraft, compatible with expected behavior of aircraft operating in the NAS. SS maneuvers "are expected to be normal/operational, non-obtrusive maneuvers which will not conflict with accepted air traffic separation standards" and made "within a sufficient timeframe to prevent activation of a collision avoidance maneuver." The maneuvers must be in accordance with regulations and procedures and compatible with TCAS II Resolution Advisories when maneuvering to avoid TCAS II equipped aircraft.

The CA function is intended to be the last layer of protection "when all other modes of separation fail" and maneuvers are made "within a relatively short time horizon before closest point of approach" (CPA).

Collision Avoidance Function

Initial guidelines of the RTCA SC-228 DAA Phase 1 draft Minimum Operational Performance Standards (MOPS) consider the CA function optional while research continues to determine if the required target level of safety in the NAS can be achieved with SS alone. In addition the draft MOPS specifies that if a DAA capability includes a CA function, it must be implemented with either a TCAS II or ACAS Xu (Aircraft Collision Avoidance System for UAS, currently under development by RTCA SC-147) CA capability with only vertical resolutions enabled. Even with this specification there are still open questions that need to be addressed to ensure the correct integration of a SS algorithm with TCAS II. Questions such as the feasibility and acceptability of automated CA maneuvers, and the coordination of integrated CA and SS alerts and maneuver guidance need to be investigated before minimum requirements can be specified.

Self-Separation Concept and "Well Clear" Volume Definition

The regulatory requirement to remain well clear of other aircraft as addressed in 14 CFR 91.113 and 14 CFR 91.111 lacks a precise or quantifiable definition of the "well clear" volume. While the regulation's language is appropriate for pilots of manned aircraft using human vision and judgment, the SS function requires an unambiguous, precise definition of what constitutes "well clear" separation in order to provide clear SS guidance to the UA pilot.

The concept described herein required that a quantified well clear definition or "self-separation volume" (SSV) be constructed satisfying the interoperability requirements mentioned before. That is, a self-separation volume must be large enough to avoid: 1) corrective resolution advisories (RAs) for TCAS II Version 7 (or higher) equipped intruders (and for the UAS if it is TCAS II equipped); 2) undue concern for proximate see and avoid pilots; and 3) perceptions of unsafe separation and traffic alert issuances by controllers.

In order to minimize TCAS corrective RA issuance, reference [1] proposed a SSV functional shape and minimum size based on the TCAS II corrective RA collision avoidance threshold (CAT), with the shape and size parameterized by threshold values of the TCAS-like variables of modified tau (ModTau), distance modification (DMOD), projected horizontal miss distance (HMD) at closest point of approach (CPA), vertical threshold (ZTHR) and time to co-altitude (TCOA).

This parameterized SSV definition has been implemented in software as part of the DAIDALUS algorithm (Detect & AvoID Alerting Logic for Unmanned Systems, previously known as Stratway+) that was developed to support the UAS integration concept evaluations.

DAA Formal analysis

The models and algorithms developed as part of the NASA UAS integration concept have undergone extensive formal analysis and verification [5, 6, 7, 8 and 9]. These models represent an essential component of the interoperability foundation of the concept, specifically, interoperability with existing TCAS II systems. As described earlier, one of the requirements in the NASA DAA concept centers on the determination of well clear values that are large enough to avoid issuance of TCAS II resolution advisories (RAs). Satisfying this requirement depends on the development of a prediction algorithm that can detect encounter geometries capable of causing RAs for TCAS II-equipped nearby aircraft, or for the UAS if it is TCAS-equipped, and provide maneuver guidance for the UAS pilot to take non-disruptive preventive actions. The TCAS RA detection model described in [8] has been developed, formally verified, and implemented in the DAA algorithm known as DAIDALUS, described below.

In addition, the formal analysis work for DAA included the identification of key properties of SSV boundary definitions that must be true of correct DAA implementations. As shown in [6 and 7], an SSV boundary definition needs to satisfy the *symmetry* property, i.e., two aircraft involved in an encounter have at all times the same perception of being well clear or not, and the *local convexity* property, i.e., for any aircraft involved in a two aircraft encounter, and for any linear projection of either aircraft trajectory there is at most one time-interval where the aircraft are not well clear. The *local convexity* property ensures that any loss of well clear separation in a non-maneuvering encounter will have a single entry point and a single exit point.

An additional property of the family of studied SSV boundary models is that they allow the decoupling of horizontal and vertical time thresholds, making it possible to eliminate either or both of the time thresholds. The current guidelines of the RTCA SC-228 DAA draft MOPS state that the vertical time threshold (referred to as TCOA) must be set to zero, thereby eliminating vertical closure rate from being used in the determination of SSV. The study conducted in [5] addresses the interoperability consequences of eliminating vertical time thresholds, particularly for encounters with high vertical closure rates. For example, it was shown that at a vertical closure rate of 3000 feet/min, a UAS relying on a SSV definition with no vertical time threshold, can still be well clear 7 s before a near mid-air collision, well after a human pilot would have likely initiated collision avoidance maneuvers. The study suggests that it would be very important to develop further understanding of the operational environment of DAA equipped UAS as well as their impact on the existing level of safety in the NAS to support the development of minimum DAA standards.

Simulation Platform

The Multi Aircraft Control System (MACS) was developed to enable human-in-the-loop (HITL) simulations of realistic air traffic scenarios including air traffic control (ATC) and pilot stations operating in structured airspace representative of today's NAS [12]. MACS was adapted and enhanced to conduct UAS research by modifying a pseudo-pilot station to simulate a UAS GCS, adding a number of new UAS performance vehicle models, a DAA capability and the displays required for the pilot in command (PIC) to perform DAA tasks.

An extensive multi-channel voice communication system was also developed to simulate aircraft-controller party-line communication on the subject sector frequency with configurable delay for UAS aircraft, and also to simulate the land-line communication channels between adjacent controllers.

Finally, the most salient enhancement of the MACS platform was the integration of the DAA algorithm known as DAIDALUS described in the next section.

DAIDALUS

A prototype DAA capability referred to as DAIDALUS (previously known as Stratway+) was designed and implemented as part of the simulation platform to conduct controller and pilot-in-the-loop experiments. DAIDALUS was developed to satisfy the operational and functional requirements detailed in NASA's DAA concept of integration for UAS [1]. The functional design, surveillance data sources, well clear separation logic, and crew interface are fully described in [10].

DAIDALUS provides algorithms that: 1) determine the current, pairwise well-clear status of the ownship and all aircraft inside its surveillance range, 2) compute maneuver guidance in the form of ranges of maneuvers that a pilot-in-command (PIC) may take that will cause the aircraft to maintain or increase separation from the well clear violation volume, or allow for recovery from loss of separation in a timely manner within the performance limits of the ownship aircraft, and 3) determine the corresponding alert type, based on the level of threat to the well-clear volume.

The maneuver guidance provided by DAIDALUS is presented in the form of *SS bands (*also known as *conflict bands)*, i.e., ranges of ownship maneuvers that lead to a well clear violation, or *recovery bands*, i.e., ranges of ownship maneuvers to recover from a present or unavoidable well-clear violation.

Both *SS* and *recovery* bands include three types of maneuver ranges: (1) track ranges (or heading, if wind information is provided), (2) ground speed ranges (or air speed, if wind information is provided), and (3) vertical speed ranges.

Conflict bands may be either preventive or corrective. A band is preventive if no well-clear violation is predicted along the ownship's velocity vector, up to the look-ahead time.

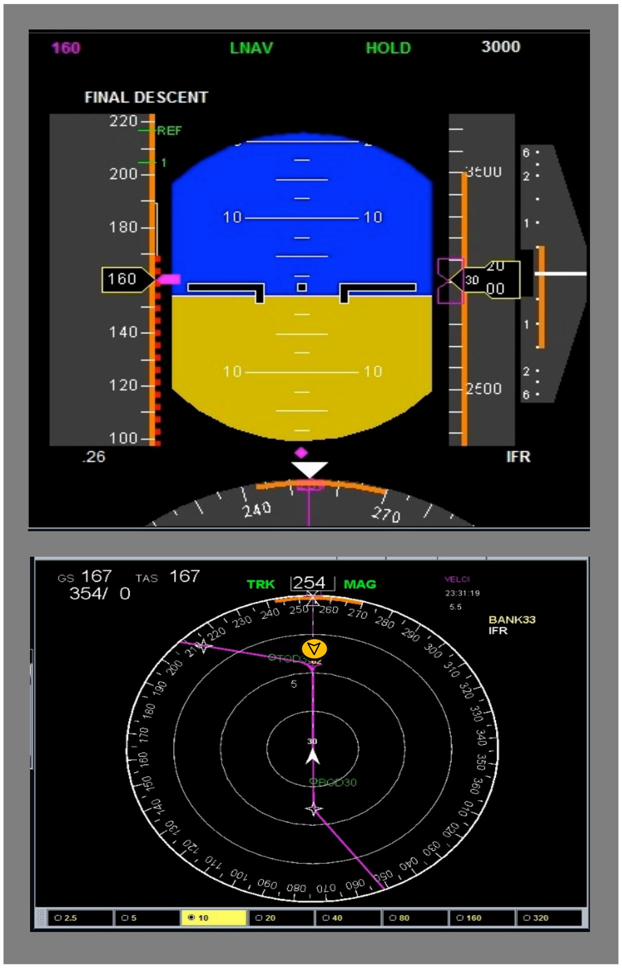

Figure 1: DAIDALUS Maneuver Guidance

Figure 1 shows all three SS bands generated by DAIDALUS. The map display at the bottom, shows the ownship (solid white symbol) at the center, the magenta line of the current ownship track and an intruder aircraft on a head-on encounter (amber symbol). A corrective SS amber heading band is shown indicating that the current heading will cause a loss of well clear separation unless the ownship maneuvers outside the indicated range. Air speed and vertical speed bands are shown on the Primary Flight Display at the top of Figure 1. The air speed band indicates that no speed change would prevent a loss of well clear separation while the vertical speed band shows that a vertical maneuver could be executed to maintain well clear (e.g., climb 500 fpm or greater).

Figure 2 shows a crossing encounter geometry in which the ownship has either lost or is about to lose well clear separation. The dashed-green *recovery* bands indicate the heading ranges to recover well clear separation.

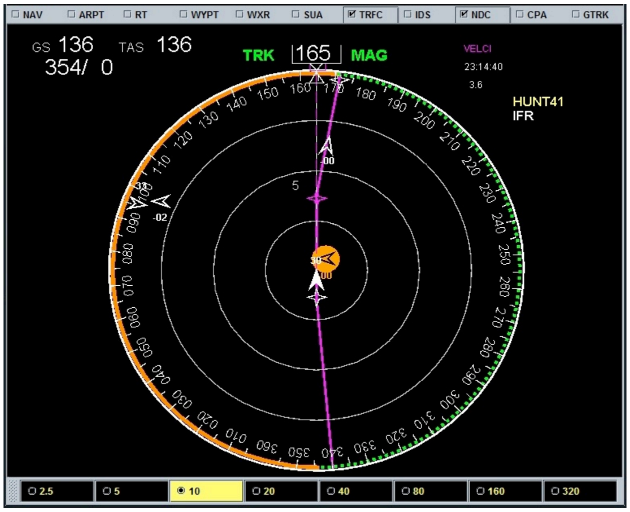

Figure 2: DAIDALUS SS and Recovery Bands

DAIDALUS also implements alerting functions that compute the alert level of intruder aircraft which are associated with maneuver guidance. The alert level represents the severity of the predicted conflict with that aircraft: the greater the numerical value, the greater the severity level. This numerical value can be interpreted and displayed to the PIC with the appropriate alert symbology. In Figures 1 and 2, the intruder's symbol indicates a corrective SS alert (CSSA). The complete set of symbols is described later in this paper.

DAA Experimental Research

The SAA concept for integration of UAS into the NAS described in [1] specified the interoperability design principles of a DAA system and identified a number of concept elements that had to be empirically assessed with both batch and HITL experiments. The research and development plan set forth included the evaluation of DAA parameters such as the acceptable SS deviations and appropriate declaration times for projected losses of well clear conditions, the impact of communication delays on pilot-controller interactions, integration of CA and SS functions, maneuver guidance, and pilot alerting effectiveness.

Controller Acceptability Study (CAS) 1

The Controller Acceptability Study 1 (CAS-1) [11] was conducted at NASA Langley Research Center from January through March 2014. CAS-1 employed 14 air traffic controller volunteers as research subjects to assess the viability of simulated future unmanned aircraft systems (UAS) operating alongside manned aircraft in moderate density, moderate-complexity Class E airspace. These simulated UAS were equipped with prototype DAA systems providing SS maneuver guidance on the experimental GCS simulation.

A quantitative CAS-1 objective was to determine horizontal miss distance (HMD) values for SS encounters that were most acceptable to air traffic controllers, specifically HMD values that were assessed as neither unsafely small nor disruptively large. To address these research questions, 84 simulated SS encounters between a UAS and a manned aircraft were constructed with different encounter geometries, HMD, and speed differentials. The SS encounters were then embedded throughout six one-hour simulated background traffic scenarios (14 encounters per one-hour scenario) representative of light-to-moderate-workload traffic in a TRACON (Terminal Radar Approach Control) area, with both Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) traffic on a calm-wind, clear-weather day. All of the SS encounters were constructed to occur in lower-altitude Class E airspace (most at 3000' with some at 4000' or 6000'). This lower-altitude, Class E TRACON airspace is arguably some of the most challenging for a SS function, other than the traffic pattern area in the immediate vicinity of an airport, since it has significant complexity with arrivals, departures, over-flights, flight training, etc.; a mix of IFR and VFR traffic with some VFR aircraft not receiving air traffic services (i.e., not on the sector frequency and not subject to controller instructions); a high incidence of see-and-avoid/SS encounters; and significant traffic flow constraints that limit options for SS maneuvers, particularly for those requiring large HMD thresholds.

All of the six one-hour scenarios ("Hours") containing the SS encounters and background traffic were constructed in the DN/AR7 sector of the D10 TRACON. Dallas-Fort Worth International Airport (DFW) is the primary airport for the D10 TRACON;

the DN/AR7 sector is in the northeast quadrant of D10 and handles south-flow traffic to/from satellite airports including Dallas Love Field (DAL), Addison (ADS) and McKinney (TKI) as well as other non-towered airports and lower-altitude en route or training flights in the sector. Simulated UAS operations included arrivals to and departures from TKI as well as overflights throughout the sector, some with a SS encounter and some not. For experiment control all UAS SS encounters were with VFR aircraft not receiving ATC services (i.e., not on the sector frequency) so a subject controller could not preemptively and strategically "fix" a SS encounter before it had a chance to occur. In most cases these encounters were also designed so that the controller could not see it developing far in advance; for example, the VFR intruder might be departing from a non-towered field and "pop up" on radar within a couple of minutes of CPA for the encounter, or alternatively might turn from a practice area toward the UAS shortly before CPA.

The primary CAS-1 dependent metric was a direct assessment of HMD acceptability by the controller subjects. The assessment was based on a five-point scale ranging from 1 to 5, in which 1 represented "too close or potentially unsafe" and 5 represented "excessively wide, potentially disruptive" separation. A total of 1176 controller assessments were obtained across all encounter geometries with a striking degree of agreement among the controller volunteers about the acceptability of 1.5 nmi HMD. Sample graphs of ATC ratings are shown in Figure 3 for opposite-direction and in Figure 4 for crossing encounter geometries. Ratings indicate that in both cases, subjects clearly favored HMDs between 1.0 and 2.0 nmi, rating smaller separation distances as "unsafe." More generally, most controllers assessed HMD values between 1 and 2 nmi to be acceptable (neither unsafely close nor disruptively large) across all encounter geometries. There was more variability in controller assessments of 0.5 nmi HMD encounters but a significant number of these assessments considered this HMD value to be too small and potentially unsafe. HMD values larger than 2 nmi were generally assessed as increasingly disruptive to orderly traffic flow.

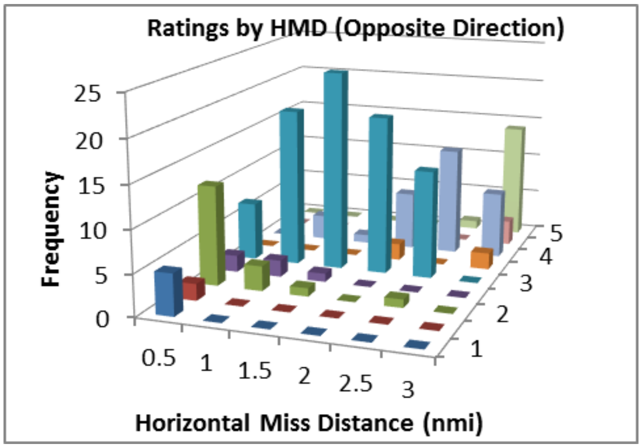

Figure 3: CAS-1 HMD Acceptability Frequency Ratings for Opposite Direction Encounters

These results should be useful to inform the development of operational performance standards for DAA SS functions. For example, it may be appropriate for standards to specify that SS functions should always indicate that SS maneuvering is necessary for encounters that will result in projected HMD values less than 1 nmi, and never indicate a required SS maneuver if the projected HMD is greater than 2 nmi.

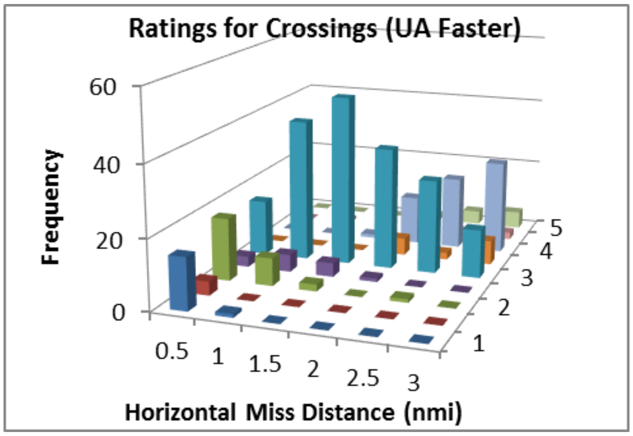

Figure 4: CAS-1 HMD Acceptability Frequency Ratings for Crossing Direction Encounters

All 14 air traffic controller volunteers were favorably impressed with the pilot-in-the-loop SS concept as simulated and presented to them, and considered the concept to be viable from an ATC perspective under the assumption that acceptable SS HMD values are employed.

Controller Acceptability Study 2 (CAS-2)

The second Controller Acceptability Study in the series was conducted in the summer of 2014. CAS-2 was based largely on the CAS-1 experiment design, scenarios, and results. This study evaluated the effects of communication delays and winds on air traffic controller ratings of acceptability of horizontal miss distances (HMDs) for different encounter geometries between UAS and manned aircraft in a simulation of the Dallas-Ft. Worth East-side airspace.

The communications delays used in this study include four different ATC-pilot communication latencies or delays that might be expected in operations of UAS controlled by combinations of ground or satellite command and control links [13]. The values used were 0, 400, 1200, and 1800 milliseconds one-way communications delays. Only a subset of the CAS-1 HMD values was used, based on the ATC acceptability ratings results from CAS-1. They were 0.5, 1.0 and 1.5 nautical miles. Wind conditions were configured with 2 values: Light (~7 knots) and Moderate (~22 knots) for all encounters that included opposite-direction, overtake and crossing geometries.

Similarly to CAS-1, the fourteen encounters per hour were staged in the presence of moderate background traffic. Seven recently retired controllers with experience at DFW served as subjects. Guidance provided to the UAS pilots for maintaining a given HMD was provided by information from self-separation algorithms displayed on the MACS GCS.

Results indicate that controllers assessed winds in simulation as realistic and UAS DAA performance acceptable; no rating differences were observed for different winds. ATC acceptability ratings of HMD values confirmed CAS-1 results, i.e., HMDs of 1.0 and 1.5 nautical miles were clearly acceptable to most controllers, while 0.5 was considered unsafe in most cases as shown in Figure 5.

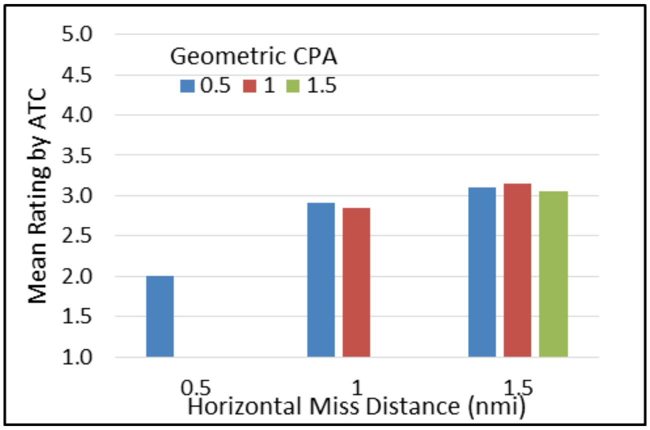

Figure 5: CAS-2 HMD Acceptability Frequency Ratings

Finally, delays of up to 400 milliseconds appear acceptable while delays of 1200 milliseconds or more appear unacceptable, causing confusion and frequent “step-ons”. Many controllers noted that such large communication delays could negatively impact safety of operations. In fact, for longer communications delays, there were changes in strategy (e.g., adapting to expected delays while talking to a UAS pilot) and communications flow that were observed and reported by the subject controllers.

Collision Avoidance-Self-Separation and Alerting Times (CASSAT) Experiment

The CASSAT experiment being conducted at NASA Langley Research Center will address minimum and maximum acceptable declaration times for projected well clear losses, from the perspectives of both ATC and the UA pilot. Some of the questions to be answered include, (1) what declaration times are excessive, leading to nuisance alerts for controllers and UA pilots and (2) what times are too short, providing insufficient time to query/negotiate maneuvers with ATC and execute them before triggering TCAS RAs? In addition, the pilot phase of the experiment will address the interoperability issues associated with the incorporation of TCAS II and SS functions as part of an integrated DAA implementation. For example, given the TCAS alerting symbology sets, does the change in display icons (between caution and warning) affect the saliency of alert levels to the UA pilot?

The CASSAT experiment comprises two phases which are based on CAS-1 and CAS-2 methodology.

Phase 1, completed in July 2015, centered on the ATC acceptability of the UAS integration concept, pilot interactions with ATC, and magnitude of UAS deviations to maintain "well clear" separation from traffic. In addition, the experiment sought to evaluate ATC's perception of conflict alerting times for projected well-clear losses provided to pilots by the DAA system. Phase 2 will be conducted between August and September 2015 and will center on the UAS pilots as subjects, seeking to validate essential elements of the DAA draft MOPS as well as to assess the integrated CA/SS DAA capability developed at NASA Langley to provide maneuver guidance and conflict alerts for predicted well-clear losses and TCAS resolution advisories (RA).

As before, the MACS simulation platform was used to simulate the DFW airspace. The scenarios were based on the ATC sector handling arrivals to Collin County Regional (now known as McKinney National – KTKI), which is approximately 28 nautical miles NE of Dallas/Fort Worth (DFW), and the surrounding airspace and airports. Traffic scenarios include 14 encounters per hour between GA aircraft that are transponding but not in voice communications with ATC or the UAS PIC. There are approximately 45 additional background aircraft per hour in the same airspace that are also in communications with the sector controller.

New elements in CASSAT's design included vertical encounter geometries and a moderate increase in traffic density. In addition, active-duty FAA controllers from facilities across the US (versus retired D10 facility controllers for CAS-1 and CAS-2) were recruited as test subjects for additional validation of CAS-1 and CAS-2 results. Finally, TCAS II Version 7.1 RA alerting logic and pilot guidance was incorporated into the simulation's DAA implementation.

CASSAT Phase 1

As mentioned before, this phase of the study focused on ATC subjects rating acceptability of UAS encounters with non-participating VFR aircraft when UAS self-separate with varied encounter geometries, HMDs and alerting times. Ten active air traffic controller subjects were provided by the FAA to participate in three-day long data collection sessions that consisted of a full day of training and 2 days of data runs.

The configuration parameters for the HMD variable were 0.7, 1.0, and 1.5 nautical miles. The range of HMD values was chosen to again validate previous experiment results as well as to support the DAA MOPS V&V process. Specifically, the 0.7 value is the SSV horizontal dimension in the draft DAA MOPS. Alerting times, i.e., the times at which the UA pilot was first shown maneuver guidance and alert symbols indicating a potential loss of well clear separation were set to 30, 45 and 75 seconds before loss of well clear (WC) separation.

In addition, another independent variable was Time to Co-altitude (TCOA) for vertical encounters (used by DAIDALUS algorithms) that was set to 0 and 20 seconds. The DAA draft MOPS requires TCOA to be 0 seconds, indicating that vertical closure rate must not be used for SSV computations. To test the potential impact of TCOA in vertical encounters, vertical rates of conflicting aircraft were set to 1000 and 3000 feet per minute. Variables from CAS-1 and CAS-2 held constant were winds, which were set to only medium wind profile for all encounters, and communications delay, which was set to 400 milliseconds for all UAS voice communications.

While data analysis is just beginning, preliminary observations and feedback from subject controllers indicate that: (1) controllers are not impacted by the conflict alerting times implemented by the DAA logic; and (2) controllers found 1.5 nautical miles (nmi) to be the most acceptable HMD, with many controllers reporting safety concerns with the 0.7 nmi HMD encounters. These results represent a major validation of CAS-1 and CAS-2 results that used recently retired ATC as opposed to active controllers. Another important finding is that TCAS RAs were generated for many of the 0.7 nmi HMD encounters and some 1.0 nmi encounters. These RAs were not acted on or reported to ATC by the staff pilots but would surely have had a further negative effect on controller acceptability ratings for the smaller HMD values. These RAs occurred with higher closure rates, e.g., head-on and crossing encounters, but the closure rates were representative of encounters expected in the simulated airspace and in all cases were less than 400 knots.

CASSAT Phase 2

The second phase of the CASSAT experiment will have UAS pilots as subjects, and air traffic controllers as staff participants supporting the experimental team. A total of fourteen pilot subjects will be part of this phase, seven of them with experience as UAS PIC and the other seven IFR certified manned-aircraft pilots.

Pilots will fly UAS scenarios with seven DAA encounters each hour in the DFW area using the MACS UAS GCS. The DAA maneuver guidance and conflict alerting will be generated by DAIDALUS for SS as previously mentioned, as well as by a TCAS II V7.1 implementation that will generate RAs if the SS maneuvers are insufficient. Two of the independent variables being manipulated for the experiment design are HMD and alerting times. In this phase HMDs will be set to 0.7, 1.0, 1.5 and 2.0 nmi. The rationale for setting the highest value in the range to be 2.0 nmi is that the preliminary values in the draft DAA MOPS for alerting indicate that the SS function shall always alert if projected HMD is 0.7 nautical miles or less and shall never alert at 2.0 or greater nautical miles projected HMD. The alerting times being considered are 40, 60 and 75 seconds prior to loss of WC separation; the lower and upper bounds of this range match the "shall always" and "shall never" alert times in the draft MOPS. Vertical encounter geometries will be modeled as in Phase 1.

For this experiment a concept for the functional integration of CA and SS functions was implemented as well as compatible SS and CA indicators and alerts. The ongoing implementation involves the integration of DAIDALUS with TCAS as a CA capability for the UA.

One key aspect of the MOPS requirements being investigated is the interoperability of integrated self-separation and collision avoidance (TCAS) guidance and alerts. A number of open issues regarding alerting symbology for SS and CA will be addressed by the CASSAT experiment. For example, is the number and nature of the SS alerts ("warning" vs. caution" level) acceptable to pilots? Is it acceptable to have a SS Warning Alert (SSWA) prior to an RA (also a Warning Alert) for transponder-equipped intruders? What is the right approach to handle multiple level conflicts in terms of both maneuver guidance and alerting scheme? Subject pilots in the CASSAT experiment will rate the acceptability, situation awareness and workload related to two candidate alerting structures for an integrated CA-SS DAA implementation. Objective pilot performance measures such as response times and well clear loss rates will also be collected. These metrics will be collected for the pilots' routine DAA encounters during their simulated-flight scenarios, but also to the extent practicable during subsequent pilot observations of recorded encounters with late-maneuvering intruders that trigger TCAS RAs and show the full range of alert symbols. One of the candidate alerting structures will match the DAA draft MOPS alerting structure for SS plus TCAS RA alerts for CA, as shown in Figure 6.

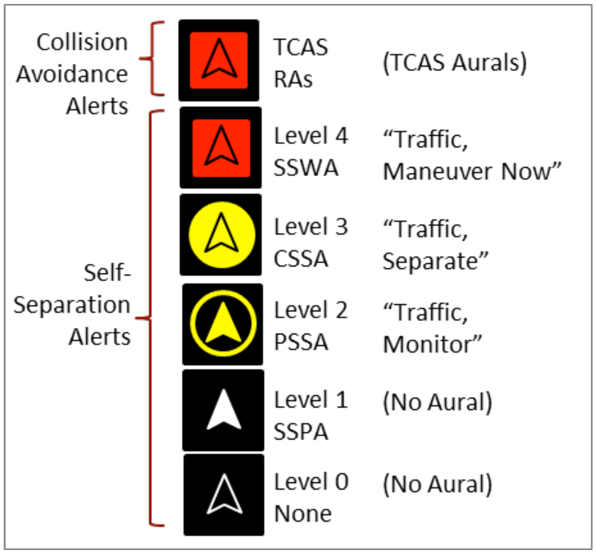

Figure 6: MOPS Alerting Structure 1

CSSA, PSSA and SSPA are Corrective SS Alert, Preventive SS Alert, and SS Proximate Alert, respectively, and are fully defined in the DAA draft MOPS, together with required configuration values (or ranges of values) for the different alerting levels, times, and distances, while research continues to verify and validate initial choices. The second alerting structure, shown in Figure 7, proposes a simplified and integrated CA-SS alerting structure (SSMA in the figure is SS Maneuver Alert and has the same intended function as SSWA, described in the draft DAA MOPS, but is renamed since it is no longer a Warning Alert).

Three key aspects of the second alerting structure are: (1) all Warning Alerts are allocated to CA (e.g., TCAS RA) making a clear symbol distinction between a CA and a SS encounter condition while all Caution and Advisory Alerts are allocated to SS; (2)

redundant alerts with the same intended function are eliminated, i.e., PSSA and SSPA in the MOPS structure, and TCAS preventive RA, require the same action by the pilot ("monitor traffic"); and (3) both CSSA and PSSA are demoted to Advisory Alerts to minimize false alerts at the Caution level while more research is performed on the frequency and impact of false/missed alerts in UAS operation in the NAS.

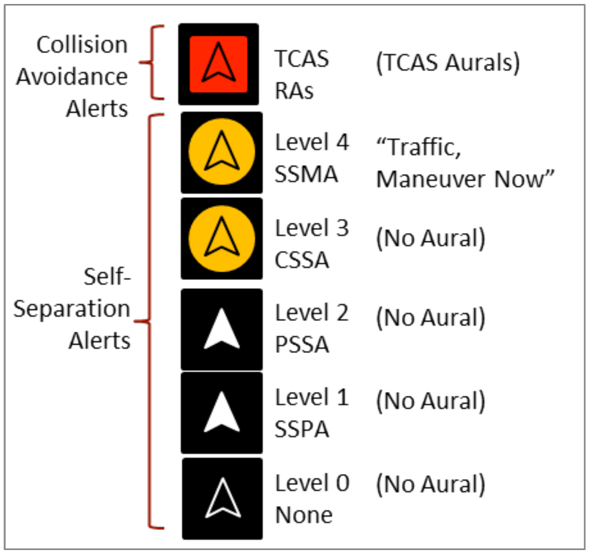

Figure 7: CASSAT Alerting Structure 2

Concluding Remarks

This paper presented an overview of research and development work conducted at NASA Langley Research Center in support of the UAS in the NAS project. Two HITL experiments, CAS-1 and CAS-2 were briefly described as well as the still ongoing CASSAT experiment, all part of the research plan designed to address interoperability and acceptability questions associated with the integration of UAS with manned aircraft operations in non-segregated airspace. Next steps in the research plan will address the impact of imperfect surveillance on SS algorithm performance. Sensor uncertainty and range limitation models will be incorporated in the simulation platform to investigate the effect of the resulting degraded maneuver guidance, and false and missed alerts on UA pilot performance.

Clearly, much research remains to be done to develop and validate the technology and operations needed for UAS integration without affecting the safety of the NAS.

References

[1] Consiglio, Maria, James Chamberlain, Cesar Muñoz, and Keith Hoffler, 2012, Concept of integration for UAS operations in the NAS, Proceedings of 28th International Congress of the Aeronautical Sciences, ICAS 2012, Brisbane, Australia.

[2] FAA sponsored Sense and Avoid Workshop, 2009, Sense and Avoid (SAA) for Unmanned Aircraft Systems (UAS). (Aka SAA First Caucus Workshop Report).

[3] RTCA-DO-304, Guidance material and considerations for unmanned aircraft systems. Prepared by RTCA SC203. March 22, 2007.

[4] RTCA-DO-320, Operational services and environmental definition (OSED) for unmanned aircraft systems (UAS). Prepared by RTCA SC203. July 10, 2010.

[5] Upchurch, Jason, Cesar Munoz, Anthony Narkawicz, Marıa Consiglio, and James Chamberlain, 2015, Characterizing the Effects of a Vertical Time Threshold for a Class of Well-Clear Definitions, Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015).

[6] Upchurch, Jason, Cesar Munoz, Anthony Narkawicz, James Chamberlain, and Mara Consiglio, 2014, Analysis of Well-Clear Boundary Models for the Integration of UAS in the NAS NASA/TM-2014-218280.

[7] César Muñoz, Anthony Narkawicz, James Chamberlain, María Consiglio, and Jason Upchurch, A Family of Well-Clear Boundary Models for the Integration of UAS in the NAS, 2014, Proceedings of the 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, AIAA-2014-2412, Atlanta, Georgia.

[8] Muñoz, César, Anthony Narkawicz, and James Chamberlain, 2013, *A TCAS-II Resolution Advisory Algorithm*, Proceedings of the AIAA Guidance, Navigation, and Control Conference (GNC), AIAA-2013-4622, Boston, Massachusetts.

[9] Narkawicz, Anthony, César Muñoz, and Gilles Dowek, 2012. "*Probably Correct Conflict Prevention*

Bands Algorithms," Science of Computer Programming, Volume 77, Issues 10-11, pp. 1039-1057.

[10] Muñoz, Cesar, Anthony Narkawicz, George Hagen, Jason Upchurch, Aaron Dutle, Maria Consiglio, and James Chamberlain, 2015 DAIDALUS: Detect and Avoid Alerting Logic For Unmanned Systems, 34th Digital Avionics Systems Conference, Prague, The Czech Republic.

[11] Chamberlain, James, Maria Consiglio, James Comstock Jr., Rania Ghatas, and Cesar. Muñoz, NASA Controller Acceptability Study 1 (CAS-1) Experiment Description and Initial Observations, NASA/TM–2015-218763.

[12] Prevot, Thomas, 2002, Exploring the Many Perspectives of Distributed Air Traffic Management: The Multi Aircraft Control System MACS, HCI-02 Proceedings, American Association for Artificial Intelligence (AAAI).

[13] Comstock, James Jr., Rania Ghatas, Maria Consiglio, James Chamberlain, and Keith Hoffler, 2015, UAS Air Traffic Controller Acceptability Study-2: Effects Of Communications Delays And Winds In Simulation, The 18th International Symposium on Aviation Psychology, Dayton, Ohio.

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