Detect and Avoid: Efforts from NASA's UAS Integration into the NAS Project

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Abstract

I. Acronyms

ACES	= Airspace Concept Evaluation System
ATAR	= Air-to-Air RADAR
ATC	= Air Traffic Control
AUVSI	= Association for Unmanned Vehicle Systems International
C2	= Command and Control
CONOPS	= Concept of Operations
C-SWaP	= Cost, Size, Weight and Power
DAA	= Detect and Avoid
DAIDALUS	= Detect and AvoID Alerting Logic for Unmanned Systems
DWC	= DAA Well Clear
FAA	= Federal Aviation Administration
GCS	= Ground Control Station
GRACE	= Generic Resolution Advisor and Conflict Evaluator
HITL	= Human-in-the-Loop
HMD	= Horizontal Miss Distance
MOPS	= Minimum Operational Performance Standards
NAS	= National Airspace System
SC-228	= RTCA Special Committee 228 MOPS for UAS
TCAS	= Traffic alert and Collision Avoidance System
TSD	= Tactical Situation Display
TSO	= Technical Standard Order
UAS	= Unmanned Aircraft System
VFR	= Visual Flight Rules

II. Abstract

NASA's Unmanned Aerial Systems (UAS) integration into the National Air Space (NAS) project has been working closely with the FAA and RTCA Special Committee 228 to identify and break down barriers to UAS integration. A focus of this work is on detect and avoid (DAA) technologies. A pilot has responsibility to see and avoid other aircraft and to remain "well clear," using their best judgment (Federal Aviation Regulations (FAR) Sec. 91.113). For UAS to perform this function, the see function is replaced by sensors to detect the other aircraft. Secondly, the pilot judgment of well clear has to be replaced by a mathematical expression. For Phase 1 of this effort, a well clear violation was defined if all three of these conditions are true: a) the horizontal clearance is less than 4000 ft., and b) the vertical clearance is less than 450 ft., and c) the time to loss of well clear is less than 35 seconds. This definition was developed with a great deal of community input and testing to ensure interoperability

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with Air Traffic Control (ATC) and pilots of manned aircraft.   Appropriate guidance, alerting and displays were developed to allow UAS, with the appropriate sensors, to effectively maintain well clear. This work contributed to FAA Technical Standard Orders: TSO-C211, Detect and Avoid and TSO-C212, ATAR for Traffic Surveillance. Phase 2 of this work extends the operational environment to include the terminal area and lesser capable aircraft that might not have the payload capability to carry the RADAR defined in Phase 1.   This session reports on work from Phase 1 and initial work in Phase 2.

III. Introduction

The Association for Unmanned Vehicle Systems International (AUVSI) published a 2013study on the economic impact of the integration of Unmanned Aircraft Systems (UAS) integration into the National Airspace System (NAS) [1]. The three major conclusions of the study were that: 1) the economic impact of the integration of UAS into the NAS will total more than $13.6 billion in the first three years of integration and will grow sustainably for the foreseeable future, cumulating to more than $82.1 billion between 2015 and 2025; 2) integration of UAS into the NAS will create more than 34,000 manufacturing jobs and more than 70,000 new jobs in the first three years; and 3) by 2025, total job creation is estimated at 103,776. The clear importance of this was emphasized by the FAA's UAS Concept of Operations (CONOPS) and Roadmap [2] that stated that, *"it is necessary to develop new or* revised regulations/ procedures and operational concepts, formulate standards, and promote technological development that will enable manned and unmanned aircraft to operate cohesively in the same airspace. Specific technology challenges include two critical functional areas: 1) Detect and Avoid (DAA) capability, and 2) Control and Communications (C2) system performance requirements."

NASA anticipated this need and formulated the UAS Integration into the NAS project that began Phase 1 in May 2011. NASA has been working closely with the FAA and RTCA Special Committee 228 (SC-228) to identify and break down barriers to UAS integration. A focus of this work is on DAA technologies. A pilot has responsibility to see and avoid other aircraft and to remain "well clear," using their best judgment [3]. For UAS to perform this function, the see function is replaced by sensors to detect the other aircraft. Secondly, the pilot judgment of well clear has to be replaced by a mathematical expression. For Phase 1 of this effort, a well clear violation was defined if all three of the following conditions are true: a) the horizontal miss distance (HMD) is less than 4000 ft., b) the vertical clearance is less than 450 ft., and c) modified tau less than 35 seconds. This definition of DAA well clear was developed with a great deal of community input and testing to ensure interoperability with Air Traffic Control (ATC) and pilots of manned aircraft. Appropriate guidance, alerting and displays were developed to allow UAS, with the appropriate sensors, to effectively maintain well clear. This work contributed to FAA Technical Standard Orders (TSOs): TSO-C211, Detect and Avoid and TSO-C212, ATAR for Traffic Surveillance [4, 5]. This paper reports on work from Phase 1 in four keys areas of research and development performed by the UAS-NAS DAA team in support of the minimum operational performance standards (MOPS) for DAA [6]: 1) DAA well clear (DWC) threshold, 2) alerting and guidance display requirements, 3) alerting and guidance processing (i.e., algorithm) requirements, and 4) validation and verification. Initial efforts by the UAS-NAS project to address Phase 2, which extends the operational environment to include the terminal area and lesser capable aircraft that lack the payload capability to carry the RADAR defined in Phase 1, is also discussed.

IV. Phase 1

Phase 1 focused on DAA system and radar/tracker requirements for UAS operations transitioning to and from Class A airspace as well as to and from special use areas.

A. DAA Well Clear

Concepts of operations for UAS in the NAS were formulated in terms of roles and responsibilities [7] and interoperability with the collision avoidance system [8]. Initial NASA work examined impacts of UAS operations on NAS traffic in terms of the number of conflicts (a function of the DWC) and the distribution of these conflicts at NAS level [9]. In order to ensure interoperability of UAS in the NAS, it was a critical consideration that the DWC threshold be small enough to not disrupt ongoing, nominal operations unnecessarily while still being large enough to ensure safety. Various forms of candidate DWC definitions were evaluated, and the frequencies of DWC violation were calculated [10]. Analytical properties required of a DWC such as symmetry and local convexity were proposed [11]. Air traffic controllers' subjective judgment of violation of a DWC was also examined [12] to help narrow down the range of acceptable DWC parameters.

NASA proposed a candidate DWC type, which along with two other candidate DWC types were evaluated with eight performance metrics [13]. NASA's simulation tool, Airspace Concept Evaluation System (ACES) [14], was used to compute two of the eight metrics. Encounter sets in ACES for metric computation were built from projected UAS traffic [15A] overlayed on historical VFR traffic. The selected DWC was further adjusted in its vertical dimension to avoid routine nuisance alerts in operations [16].

B. Alerting and Guidance Display Requirements

The UAS-NAS DAA subproject conducted a series of human in the loop (HITL) simulation experiments, resulting in empirical data that informed the development of the display requirements within the DAA MOPS [17, 18, 19, 20, 21]. The objectives of this set of experiments was twofold: 1) to determine the minimum set of display requirements that would support acceptable pilot performance in remaining DAA well clear of other aircraft, and 2) to determine the amount of time within the DAA timeline that needed to be allocated to the pilot response time. The first objective drives the minimum information requirements for the DAA display, including information elements, alerting and decision aiding such as maneuver guidance. The second objective drives other DAA system requirements that need to account for human response times, such as the minimum range of the onboard surveillance equipment and appropriate alerting thresholds.

In order to fulfil these two above objectives, the DAA team developed two categories of metrics to objectively quantify pilot performance on remaining DAA well clear. The first category, measured response, quantifies a human operator's end to end response time for a task by breaking down that response into discrete stages [22, 23]. Fern et al. [17] defined the measured response timeline and stages for a pilot responding to the presence of a DAA alert. By extracting various response times between different stages of the response timeline, the impact of different display configurations on pilots' response can be quantified and compared. These metrics capture how quickly pilots respond given a DAA display configuration as well as how much time needs to be allocated to the pilot in the DAA timeline. The second category of metrics used to measure pilots' performance is loss of DAA well clear. These metrics include the proportion of actual to predicted losses of DAA well clear, the severity of losses of DAA well clear that occur (i.e., how much of the DAA well clear threshold was penetrated), and the causes of losses of DAA well clear. The loss of DAA well clear metrics indicate how well pilots are remaining DAA well clear of other aircraft as well as help diagnose why losses of DAA well clear occur.

Using the measured response and loss of DAA well clear metrics, various DAA display features were compared during the HITL experiments to examine the impact on pilots' ability to remain DAA well clear in order to determine the minimum display requirements for safe operation of the DAA system. Across the series of HITL experiments, the following display features were examined: 1) if and how maneuver guidance should be presented to the UAS pilot situation in the ground control station (GCS) [17, 18, 19]; 2) multi-level alerting structures [24; 3) the level of display integration in the GCS (e.g., integrated into the primary GCS display versus in a separate, standalone display) [17, 20]; and 4) interoperability of DAA alerting and guidance features with the Traffic alerting and Collision Avoidance System (TCAS) II alerting and guidance [21].

C. Alerting and Guidance Processing Requirements

NASA contributed to the requirements of the detect and avoid alerting and guidance requirements. Prototype DAA algorithms such as the Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) [25] and the Generic Resolution Advisor and Conflict Evaluator (GRACE) [26] were developed to support research and requirement work. DAIDALUS became the reference DAA implementation for the DAA MOPS. ACES simulations provided a set of encounters that allowed researchers to relate alerting criteria to sensor range requirement [27]. Trade space between alerting metrics such as false positive alert and missed alert, as well as different effects of state-based and flight-plan-based trajectory predictions on alerting and guidance performance [28], were investigated. Researchers assessed the adequacy of DAA's alerting timeline by recording when and where air traffic controllers issued traffic alerts and advisories during encounters [29]. A method of accounting for sensor uncertainty was investigated [30].

For DAA guidance, an analytical study illustrated the relationship between aircraft performance parameters and the required maneuver initiation range [3031, 32]. Interoperability of DAA vertical guidance with TCAS II was investigated, and a collision avoidance region was recommended to RTCA [33]. The effectiveness of vertical guidance against non-cooperative intruders was investigated [34].

D. Validation and Verification

DAA Flight tests demonstrate that concepts of operation, combined with integrated the DAA and C2 technologies, actually work. NASA conducted Flight Tests 3 [35] and 4 [36] in which prescribed encounters involving NASA's test UAS Ikhana and manned aircraft intruders were flown. The Live, Virtual, Constructive Simulation Environment (LVC) [37] served as a message switchboard for communications and data collection. Results were analyzed [38, 39, 40] to validate simulation results and inform the MOPS development.

An end-to-end fast-time simulation near the end of Phase 1 work was conducted [41] to verify and validate the performance of a DAA system, utilizing the reference DAA implementation (DAIDALUS), sensor and tracker models, a pilot response model, and the test vector encounters. A HITL simulation was also conducted to verify and validate of the proposed DAA display requirements [20**]**.

V. Phase 2

One of NASA's research areas in Phase 2 work is to help enable UAS operations with low cost, size, weight, and power sensors (C-SWaP). The ATAR specified in the Phase 1 MOPS is the only sensor onboard that can detect non-cooperative aircraft. However, the Phase 1 ATAR must detect intruders 8 nmi away and thus requires high power. For many UAS missions that fly at low speeds and altitudes, the Phase 1 ATAR is either physically infeasible or economically impractical. To enable additional missions of UAS that are equipped with relatively low C-SWaP sensors, NASA has partnered with Honeywell International with a cooperative agreement since 2017. Flight tests are being planned for demonstrating DAA capabilities using a NASA UAS, SIERRA-B, that will be equipped with Honeywell's proprietary low C-SWaP radar. In the meanwhile, NASA has started investigating alternative forms of Well Clear definitions [42, 43] for UAS and non-cooperative aircraft. In support of this work, NASA has performed an analysis to provide insight into the trade space between UAS speed and turn capability and DAA sensor range requirements [44].

NASA is researching needed modifications to the DAA well clear parameters and alerting times to enable terminal operations. Two NASA studies provided empirical evidence that the Phase 1 DWC parameters are too large for terminal operations and cause excessive alerts for traffic entering or within the VFR traffic pattern while an arriving UAS is as far as 8 nmi from the runway, resulting in degraded pilot performance [45, 46]. NASA conducted a fast-time simulation that investigated a wide variety of DWC parameters in an effort to determine under what conditions alerting and losses of DAA well clear occurred for traffic entering or within the VFR traffic pattern [47]. NASA will evaluate alerting times associated with the final terminal DWC parameters as well as methodologies for switching from the Phase 1 DWC parameters to the terminal DWC parameters.

In an effort to address issues with the Phase 1 sensor uncertainty mitigation approach when the sensor uncertainty is very large, NASA will investigate alternative approaches involving integrating sensor uncertainty mitigation into DAIDALUS.

NASA has been assisting the FAA in verifying and validating the performance of ACAS-Xu, an UA-variant of ACAS that will replace TCAS to be the next-generation collision avoidance system. ACAS-Xu has been in active development to incorporate DAA capabilities, building towards the Phase 1 MOPS. NASA worked with the FAA in conducting a flight test in 2017 and performed limited-scope data analysis [48]. NASA will evaluate display options for ACAS-Xu with a HITL.

Ground-based DAA utilizes surveillance systems on the ground to perform DAA and is particularly suitable for terminal area operations. NASA funded Virginia Tech Test site to conduct a flight test with ground-based radars as the surveillance system. Data will be collected via the LVC test infrastructure and a generic ground-based sensor model will be developed.

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