UAS Pilot Assessments of Display and Alerting for the Airborne Collision Avoidance System X_U

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Unmanned aircraft systems (UAS) must comply with specific standards to operate in the National Airspace System (NAS). Among the requirements are the detect and avoid (DAA) capabilities, which include display, alerting, and guidance specifications. Previous studies have queried pilots for their subjective feedback of these display elements on earlier systems; the present study sought pilot evaluations with an initial iteration of the unmanned variant of a Next Generation Airborne Collision Avoidance System (ACAS X_U). Sixteen participants piloted simulated aircraft with both standalone and integrated DAA displays. Their opinions were gathered using post-block and post-simulation questionnaires as well as guided debriefs. The data showed pilots had better understanding and comfort with the system when using an integrated display. Pilots also rated ACAS X_U alerting and guidance as generally acceptable and effective. Implications for further development of ACAS X_U and DAA displays are discussed.

INTRODUCTION

Since the early 2000s, the integration of unmanned aircraft systems (UAS) into the National Airspace System (NAS) has been an ongoing effort of the UAS community and participating organizations **(**FAA, 2018; Fern et al., 2014**)**. A significant technological challenge for UAS integration is compliance with the "see and avoid" requirement that is mandated under section 91.113 of Title 14 Code of Federal Regulations (2004, p. 830). Translated into unmanned systems, the concept of see and avoid is expressed as detect and avoid (DAA); this involves equipping UAS with hardware and software that allow a ground pilot to maintain 'well clear' (WC) from other aircraft. The development of Minimum Operational Performance Standards (MOPS) for UAS DAA systems has been pioneered by RTCA Special Committee 228 (FAA, 2018; RTCA, 2013).

NASA's UAS Integration into the NAS Project has supported the development of the UAS DAA MOPS through fast-time, human-in-the-loop (HITL) simulations, and flight testing. The HITL simulation efforts have largely focused on the effects of controls and displays on the quality and timeliness of pilot responses to scripted traffic conflicts. This has been accomplished using multimodal alerting and guidance from ground control station (GCS) interfaces (Rorie et al., 2016; Rorie et al., 2017). Some of these studies specifically explored pilot performance as the result of where the DAA information was located, either separated from the primary navigation display and interfaces (i.e., standalone) or collocated with them (i.e., integrated, Fern et al., 2014).

While the work on UAS DAA systems is relatively recent, there is a long and established history of research into collision avoidance (CA) systems in aviation. In the 1970s one of the earliest iterations was the Beacon Collision Avoidance System (BCAS) designed for lower-density airspace. Shortly afterward, the second iteration, the Traffic Alert and Collision Avoidance System (TCAS), was designed for higher-congestive airspace. Limitations of the first version of TCAS were the inabilities to recognize certain contexts in airspace environments and an incapacity to anticipate certain pilot behaviors (Kochenderfer et al., 2012). TCAS II expanded on the alerting offered by TCAS I by adding Resolution Advisories (RAs), which directed pilots to perform specific maneuvers when a near midair collision (NMAC) was imminent (Burgess et al., 1994). TCAS II was widely adopted and was required worldwide for certain larger aircraft by the end of the 1900s (Eurocontrol, 2017).

Neither TCAS I nor TCAS II can detect and provide guidance horizontally. TCAS III attempted to remedy this, but development was discontinued when the system's antennae could not accurately accommodate a horizontal dimension (Burgess et al., 1994). TCAS IV provided a second attempt by utilizing data from other sources like automatic dependent surveillance–broadcast (ADS-B) and the global positioning system (GPS). In addition to the difficulty of providing support horizontally, all versions of TCAS required performance envelopes that were only available in larger and more powerful aircraft; this prohibited them from operating in UAS with low size, weight, and power, also referred to as low SWaP (Kochenderfer et al., 2012).

The limitations of TCAS necessitated the design and development of the Airborne Collision Avoidance System (ACAS) in the 1980s (Eurocontrol, 2017). The recent ACAS X iteration has been adapted to the Next Generation Air Transportation System (NexGen), and versions of it include those modified for active surveillance (ACAS X_A), operational specificity (ACAS X_O), UAS (ACAS X_U), small UAS (ACAS $_sX_U$), and rotary-wing aircraft (ACAS X_R; Eurocontrol, 2017; RTCA, 2019). Similar to versions of TCAS, ACAS uses programmed logic to predict positions and directions of aircraft. It also works with transponders that can communicate between aircraft, and it is compatible with both GPS and ADS-B. Unlike TCAS however, the current versions of ACAS use algorithms that also utilize combinations of other types of surveillance, like infrared and electro-optical sensors. The combinations of these provide superior protection against ‘non-cooperative’ (i.e., non-transponding) aircraft. ACAS’s logic has also been modified to accommodate models of current and anticipated national airspace configurations. Additionally, it can seamlessly provide detection and guidance in both horizontal and vertical dimensions. Finally, ACAS reduces the number of alerts it issues relative to TCAS. The results are a more capable system that has lower adoption and maintenance costs and can be utilized with low SWaP aircraft (ICAO, 2006; Kochenderfer et al., 2012).

The current project builds upon similar studies that examined locations and contents of DAA displays within earlier systems (Fern et al., 2014; Monk et al., 2015; Rorie et al., 2016; Rorie et al., 2017; Santiago et al., 2015). This was accomplished by gathering pilots’ subjective feedback, during a HITL simulation, using ACAS X_U as the DAA system. These subjective findings are presented below. The objective findings to this study were published in a separate report (Rorie et al., 2020).

METHOD

Participants

Sixteen active duty UAS pilots were recruited (M_{age} = 34 years old, SE = 8.38). Their manned flight time totaled over 1,600 hours in civilian aircraft and over 11,000 hours in military flights. From the military operations, over 3,000 hours were flown in combat. Their unmanned flight experience totaled over 16,000 hours, over 14,000 of which were combat related. Most held several ratings and had experience piloting multiple types of aircraft.

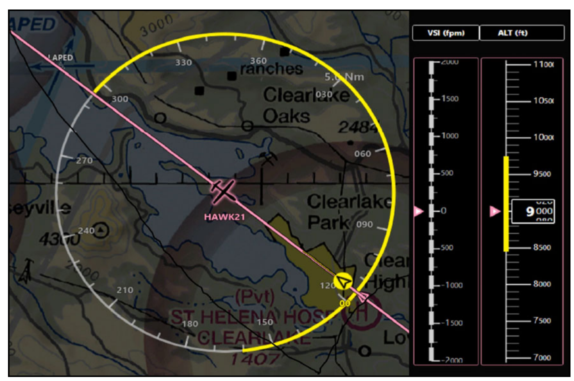
Apparatus

Simulation. The Vigilant Spirit Control Station (VSCS), developed by the Air Force Research Laboratory, was used as the GCS in the current study (Feitshans et al., 2008). Since its inception, VSCS has been modified to conform to the UAS DAA MOPS to the greatest extent possible. Participants were situated at the VSCS in an enclosed room, accompanied by a single experimenter. This experimenter acted as an observer and assistant when needed by the participant. In a separate room, ‘pseudo’ pilots and a confederate air traffic controller (ATC) used the Multi Aircraft Control System (MACS) to create representative NAS operations virtually (Prevot, 2002). The MACS environment was configured to replicate Oakland Center Class E airspace. Participants, pseudo pilots, and ATC communicated via radio over a common frequency.

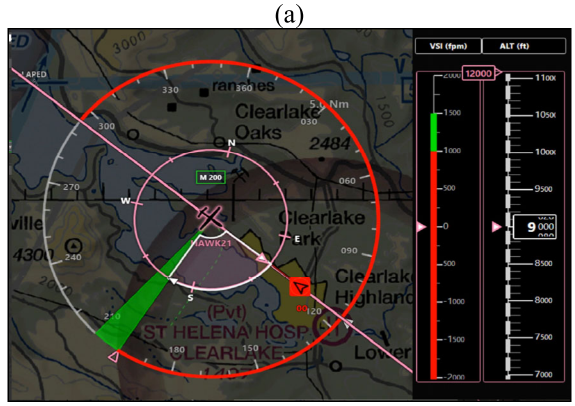
DAA System. The current study utilized ACAS X_U to generate collision avoidance and DAA alerting and guidance. Alerts, icons, and bands were color-coded based on the proximity of traffic. Table 1 shows examples of intruder symbols and their corresponding pilot actions. Background aircraft were displayed in black and white. Preventive and Corrective-level encounters provided maneuver guidance and were displayed with caution-level (i.e., yellow) icons and banding (Figure 1a). RAs provided maneuver directives and were accompanied by warning-level (i.e., red) icons and banding (Figure 1b). RAs also displayed a directional indicator using a green ‘wedge’ to highlight the desired maneuver direction. RAs could be either horizontal (i.e., issued a target heading), vertical (i.e., issued a target vertical speed), or blended (i.e., issued both a target heading and vertical speed). The target heading and vertical speed values could be updated as frequently as every five seconds during an active RA. Updates to the target heading occurred more frequently than updates to the target vertical speed, and therefore horizontal RAs were much more common in the present study.

Icon	Alert Level	Pilot Action	Aural Alert
	Resolution Advisory (RA)	• Immediate action required • Must upload within 5 seconds • ATC coordination after	“Climb/Descend” and/or “Turn Left/Right” (x2)
	Corrective DAA Alert	• Action required for DAA WC • ATC coordination before	“Traffic, Avoid”
	Preventive DAA Alert	• No action required • Possible increase to Corrective	“Traffic, Monitor”
	Guidance Traffic	• No action required • Possible increase to Preventive	N/A
	Other Traffic	• No action required • No coordination required	N/A

Table 1. ACAS X_U alerting structure.



(a)



(b)

Figure 1. (a) An active DAA Corrective alert (yellow banding and icon), (b) An active Resolution Advisory (red banding and icon, green wedge).

Experimental Design

The current study used the DAA display configuration as a two-level, within-subjects variable. Both display types showed the same amount of information, including the general aircraft telemetry, horizontal range rings, an altitude tape, navigation menus, an area map, and ownship position and direction. The location of the DAA information, however, differed in each configuration, as shown in Figures 2a and 2b.

Integrated. The integrated condition consisted of a status panel and tactical situation display (TSD). The status panel showed the mission checklist, chat, and other aircraft information. The TSD showed maps, traffic, vehicle control interfaces, and DAA alerts and guidance (Figure 2a).

Standalone. The standalone configuration had the same status panel as the integrated condition. The TSD, however, only showed maps and vehicle control interfaces whereas the traffic, DAA alerts, and guidance were moved to a separate, dedicated display (Figure 2b).

In addition to DAA display configuration, the encounter type and intruder equipage were manipulated within-trial. Traffic conflicts were scripted to either appear first as a DAA Corrective alert or as an RA. Intruder equipage was either 'cooperative' (i.e., detected using a simulated ADS-B) or 'non-cooperative' (i.e., detected using a simulated on-board radar).

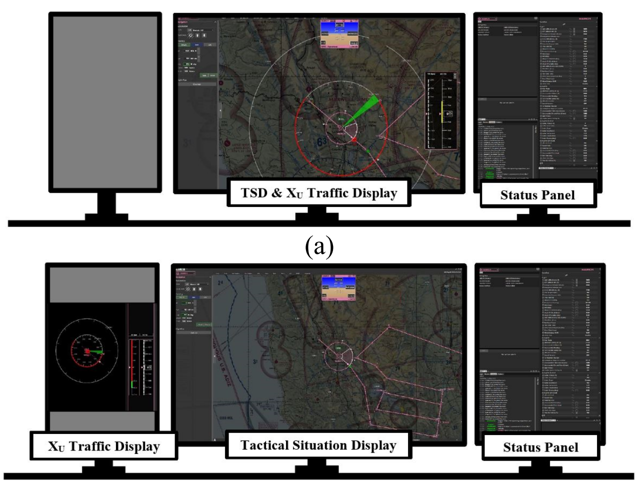


Figure 2. (a) Integrated configuration, (b) Standalone configuration.

Procedure

Training. Participants first completed informed consent and demographic forms, followed by a combination of presentations and hands-on training with the system. Presentations included background and contextual information, and hands-on training familiarized pilots with controlling their simulated aircraft and responding to practice encounters. This continued until pilots demonstrated proficiency and comfort with the system and workstations. Each morning training session lasted approximately 90 minutes.

DAA Pilot Task. Pilots were instructed to control a simulated MQ-9, using a mouse and keyboard configuration, along pre-programmed flightpaths. Each pilot completed two different paths for each of the two configurations – totaling four trials, or 'runs,' per participant. The scenarios were counterbalanced, and each lasted approximately 45 minutes. The participants' primary responsibilities were to fly their UAS under instrument flight rules (IFR) and to do so while maintaining well clear from other aircraft using the information from ACAS X_U. Each trial consisted of six scripted encounters, each of which were designed to collide with the UAS absent corrective action. Pilots were responsible for manually responding to Corrective alerts. In contrast, VSCS automatically entered target RA headings and altitudes (VSCS does not allow direct vertical speed commands) into the auto-pilot interface. Pilots were still responsible for reviewing the RA and uploading it to the aircraft as quickly as possible by clicking "Send" on VSCS. The intent of the auto-loading behavior was to assist pilots in complying with the RA response time requirements of 5 seconds for initial RAs and 2.5 seconds for subsequent RAs (Eurocontrol, 2017; ICAO, 2006). Pilots were instructed to coordinate with ATC before executing maneuvers for Corrective alerts, and to advise the controller after executing RAs. Lastly, pilots were directed to comply with secondary tasks, time permitting, which included attending to chat messages and resolving aircraft health and status alerts.

MEASURES

For subjective feedback, each pilot completed a post-block questionnaire, post-simulation questionnaire, and post-simulation debrief.

Post-Block Questionnaire

Pilots answered a questionnaire upon completion of two successful trials, or one block. Because each block explored a single configuration, the post-block questionnaires compared responses against standalone and integrated displays. The post-block questionnaire included two portions:

NASA TLX. The first portion required pilots to rate six factors, on a seven-point scale, using the NASA Task Load Index (TLX, Hart, 2006): mental demand, physical demand, temporal demand, performance, effort, and frustration.

Post-Block Questions. The second portion involved 11 questions that collected pilot reaction to ACAS training, traffic, alerting, and guidance. Most of the questions were rated on a 5-point Likert scale, which ranked responses from Strongly Disagree (1) to Strongly Agree (5). Unless otherwise specified, all 5-point scales for this study followed the same format.

Post-Simulation Questionnaire

After four completed trials, pilots completed a survey that measured their impressions of the ACAS X_U system. These were composed of 32 questions regarding the presentation of guidance, alerts, advisories, and sensor noise. Some of the questions were categorized based on themes like timing, stability, clarity, effectiveness, reasonability, and comfort. Other questions regarded functions of the system that were not available, yet may have been desired, like textboxes or automatic executions of the maneuvers. Most of the questions were also rated on the 5-point Likert scale. Unlike the post-block questionnaires, most of the post-simulation responses did not specify the differences between the standalone and integrated displays; the exceptions were three questions that specifically measured overall comfort and preference for the two configurations.

Debrief

At the conclusion of the study, pilots were led through a guided conversation about their overall experience in the simulation. The conversation consisted of open-ended questions that encouraged pilots to further elaborate on responses given in the questionnaires. These also allowed pilots to provide any additional information that may not have been considered by the experimenters.

RESULTS

Software-based data collection tools omitted a small number of responses that were not recorded; these are reflected as reduced degrees of freedom in the results below. From the responses that were successfully gathered from the post-block questionnaires, two-tailed, paired t-tests were performed using an alpha level of 0.05. Comparisons of means were used to analyze responses to the post-simulation questionnaires. The information collected from debriefs expounded on some of the statistical data retrieved from the survey-based questionnaires.

Post-Block Questionnaire

Task Load. Display configuration significantly affected pilots' perception of mental demand and frustration. Specifically, mental demand was rated as higher while using the standalone display (M = 3.40, SE = 0.19) than the integrated display (M = 2.87, SE = 0.13), $t(14) = 2.779$, p = 0.015. Frustration was also rated significantly higher in standalone (M = 2.43, SE = 0.27) versus integrated configurations (M = 1.79, SE = 0.21), $t(13) = 2.223$, p = 0.045. The display condition was not shown to have a significant effect for any of the other TLX factors.

Post-Block Questions. Training was declared as sufficient for both integrated (M = 4.93, SE = 0.07) and standalone (M = 4.80, SE = 0.11) displays. Pilots also trusted the accuracy of the traffic information for integrated (M = 4.40, SE = 0.21) and standalone (M = 4.40, SE = 0.29) displays. Significance was present in the effects of display configurations on system comprehension and perceived pilot performance: The ACAS traffic information was easier to understand in the integrated display (M = 4.87, SE = 0.09) versus the standalone (M = 4.20, SE = 0.26), $t(14) = -2.32$, p = 0.036. Similarly, it was also easier to understand Corrective alerts and guidance in the integrated display (M = 4.60, SE = 0.13) than in the standalone display (M = 4.13, SE = 0.26), $t(14) = -2.17$, p = 0.048. Furthermore, pilots reported that the location of the traffic in the integrated display (M = 4.80, SE = 0.11) better supported their ability to maintain separation versus standalone (M = 3.33, SE = 0.35), $t(14) = -3.67$, p = 0.003.

Post-Simulation Questionnaire

Averages of the overall results revealed that all participants found the timing of the ACAS X_U alerting and guidance to be ideal, on a 3-point Likert scale (1=Too Early, 2=Ideal, 3=Too Late), (M = 2.31, SE = 0.08). On the five-point Likert scale, pilots agreed that the alerting and guidance was clear (M = 4.15, SE = 0.20), reasonable (M = 4.10, SE = 0.15), and effective (M = 4.54, SE = 0.12). Pilots also declared that preventative alerts were stable (M = 4.06, SE = 0.17) as well as Corrective alerting (M = 4.38, SE = 0.20) and guidance (M = 4.25, SE = 0.19). On average, pilots were largely undecided regarding stability of the RAs (M = 3.81, SE = 0.28). When pilots were asked two questions indicating their comfort levels with both configurations, they acknowledged that they would be more comfortable flying with the integrated display (M = 4.69, SE = 0.20) over the standalone display (M = 3.75, SE = 0.35) (Figure 3). When asked a single question that required a decision between the two configurations, 88% of the pilots chose the integrated display (Figure 4).

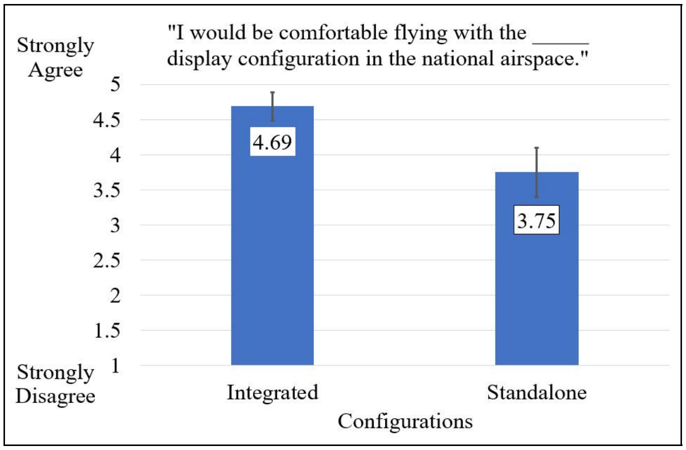


Figure 3. Comfortability ratings by display configuration.

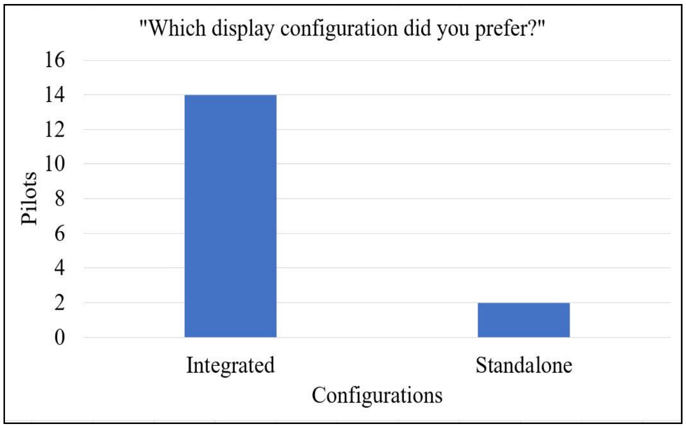


Figure 4. Preference ratings by display configuration.

Extra functionalities. On average, participants were indifferent to, or disagreed with, adding functions like a clear-of-conflict aural alert (M = 3.44, SE = 0.35) as well as text boxes containing RA information in the integrated (M = 2.63, SE = 0.30) or standalone (M = 3.00, SE = 0.32) configurations. The same was true regarding automatic executions in integrated (M = 2.50, SE = 0.42) or standalone (M = 2.50, SE = 0.42).

DISCUSSION

The findings favored the integrated display, which coincides with previous studies that found an integrated display preferable (although the trends were not significant in those studies, Monk et al., 2015; Rorie et al., 2017). Presenting DAA traffic information, along with the steering interface, on a single display protects against having to partition attention across separate screens. Nonetheless, five pilots still claimed that the standalone display was acceptable in some circumstances – like when too much data could overload a single screen. Future studies could explore interchangeable displays that allow the pilots to choose between integrated and standalone configurations when desired.

Overall, pilots found the alerting and guidance generated by ACAS X_U to be effective and reasonable. While pilots found the Corrective guidance to be stable, the ratings were less positive for the stability of RA guidance. This is likely a reflection of the frequency with which RA target headings updated over the course of a given encounter. In debriefs, pilots reported that they found it unnecessary to comply with the new target headings since the vehicle was sometimes in a turn already when updates were issued, and thus they were considered redundant. Most pilots were accepting of the auto-loading feature that was employed for RAs. This was provided to facilitate faster response times while still ensuring the pilot had the final authority on uploading a command to the aircraft. Interestingly, most pilots challenged the idea of fully automating the RA responses presently. According to pilot feedback, they prefer to retain authority on collision avoidance maneuvers to prevent undesirable vehicle responses. Some pilots however, claimed that an auto-execute function would be acceptable in some circumstances – as long as automation first received the approval of the pilot in command. Therefore, auto-execution may also be a topic deserving of exploration in future studies.

While pilots rated ACAS X_U favorably, their objective performance while using the system must also be understood. The objective findings of the current HITL simulation were published separately (Rorie et al., 2020).

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