Display and Automation Considerations for the Airborne Collision Avoidance System Xu

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In this paper we examine several display and automation considerations of a collision avoidance system that is currently under development: the Airborne Collision Avoidance System (ACAS) Xu. This study builds on previous work conducted as part of NASA's Unmanned Aircraft Systems (UAS) Integration into the National Airspace System (NAS) project. ACAS Xu represents the next-generation successor to the Traffic Alert and Collision Avoidance System (TCAS II), wherein the Xu variant is intended for UAS applications. Whereas TCAS II exclusively issues RAs in the vertical dimension, a major distinction between ACAS Xu and previous collision avoidance (CA) systems is the introduction of horizontal and "blended" RAs (i.e., RAs with both horizontal and vertical components). This present work was conducted as an engineering analysis involving two parts. In Part 1, a two-by-two, within-subjects study was performed that manipulated how RAs were presented to a pilot situated at a UAS ground control station. Five participants experienced four experimental trials in which text and aural alerting characteristics were manipulated. In Part 2, another five participants experienced four trials in which the levels of automation were manipulated with regard to the CA and return-to-course (RTC) tasks. The results for Part 1 found no effect of display or alerting configuration on pilot performance. However, it was discovered that pilot response time to RAs greatly depended on the RA type. In particular, pilots were quicker to respond to vertical RAs (*M* = 4.52 seconds) than horizontal (*M* = 7.42 seconds) and blended (*M* = 9.68 seconds) RAs in which both dimensions were issued simultaneously. For Part 2 of the study, pilots found both auto-CA and auto-RTC functions equally useful. Most pilots were comfortable with the automation, however responses were mixed. Three of five participants indicated high levels of comfort with the auto-CA function, while two rated their comfort as low. Pilots' comfort for the auto-RTC functionality was slightly higher: four out of five pilots gave high ratings, while one pilot gave a low rating. Overall, pilots ordinally ranked their preference for automated functions as auto-CA together with auto-RTC (when an aural alert announces a change between CA and RTC states), auto-CA, and auto-CA and RTC (without the aural state-change announcement). Recommendations for improving the display of automation are also discussed.

I. Introduction

Since 2011, NASA's Unmanned Aircraft Systems (UAS) Integration into the National Airspace System (NAS) project has examined the challenges surrounding flying unmanned aircraft in the same category of airspace as commercial and general aviation operations. A crucial component of this work is the development of technical

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standards necessary for a sufficient detect and avoid (DAA) system. This system provides a remote UAS pilot with alerting and guidance within a ground control station (GCS) to stay safely separated from nearby traffic should such a loss of "DAA well clear" be predicted to occur. The DAA system relies on a variety of surveillance sources (e.g., ADS-B and air-to-air RADAR) to allow for compliance with the "see and avoid" requirement (14 CFR Part 91) for current operations with an onboard pilot [1]. The variety of surveillance sources ensures that the DAA system can protect against all nearby aircraft, regardless of the equipage of surrounding vehicles. While all DAA systems protect against losses of DAA well clear, they can differ in important ways. One crucial difference is whether a DAA system protects only against the DAA well-clear threshold or if it also supports a Collision Avoidance (CA) function, which adds a second layer of protection around the near midair collision (NMAC) volume. Radio Technical Commission for Aeronautics (RTCA) Special Committee 228 (SC-228), which has been developing the UAS DAA Minimum Operational Performance Standards (MOPS), identifies three different DAA classes that vary along this dimension [2]. Class 1 DAA systems refers to platforms that only provide protection against DAA well clear. Class 2 systems pair the DAA system with the Traffic Alert and Collision Avoidance System (TCAS II), a CA system that has been in use for decades. In contrast, Class 3 systems utilize the UAS variant of the Airborne Collision Avoidance System (ACAS Xu) to provide both DAA and CA functionalities. ACAS X is a next-generation CA system that is currently under development and has different variants for different platforms.

The UAS Integration into the NAS project has conducted numerous studies aimed at testing and validating Class 1 display, alerting, and guidance requirements in human-in-the-loop (HITL) simulations [3-7]. Through this and other work performed by members of RTCA SC-228, a minimum set of DAA alerting and guidance requirements were established. These requirements include a multi-level alerting structure that consists of two caution-level alerts and a single warning-level alert, each with associated symbology and aural annunciations that cue the pilot to intruders predicted to lose DAA well clear. The DAA guidance requirements specify the use of caution- and warning-level "suggestive" guidance, that indicate to the pilot which trajectories are, and are not, predicted to lead to a loss of DAA well clear. Taken together, these alerting and guidance requirements were found to reduce pilot response times, reduce the frequency and severity of losses of DAA well clear, and lead to high levels of pilot acceptability and ATC coordination [7].

The initial DAA alerting and guidance requirements were designed specifically for Class 1 systems. These requirements had to be re-examined within the context of Class 2 systems, which supplement the DAA system with TCAS II, which has its own set of alerting and guidance requirements. As part of its alerting and guidance, TCAS II issues "directive" vertical resolution advisories (RAs) that command a target vertical rate. Such guidance needs to be accommodated by the multi-level alerting and "suggestive" guidance schema utilized by the DAA system. Furthermore, TCAS II cannot protect against non-cooperative (i.e., non-transponding) intruders, since it relies on active surveillance, whereas the DAA system can detect non-cooperative intruders with its airborne (or ground-based) radar. The UAS Integration into the NAS project conducted a human-in-the-loop simulation to test potential mitigations to the numerous interoperability challenges that arise with the integration of these two systems [8]. The mitigations included changes to both systems' alerting and guidance structures that were designed to simplify the presentation of alerts and prevent potentially conflicting guidance. The results of the study showed that pilots ultimately understood the provided guidance and were able to consistently maintain DAA well clear and comply with TCAS II RAs as necessary. Nonetheless, the interoperability requirements were unable to resolve the fundamental problem that the TCAS II system is "blind" to a subset of the intruders that can be detected by the DAA system.

Class 3 systems overcome this core limitation by incorporating non-cooperative surveillance sources (e.g., air-to-air RADAR) in addition to ADS-B and active surveillance to generate DAA alerting and guidance as well as RAs. ACAS Xu also modified the DAA alerting structure to simplify the number and type of alerts. For instance, ACAS Xu does not issue a DAA warning alert or warning-level DAA guidance, replacing it instead with an RA that is issued at approximately the midpoint between when a DAA warning alert and a TCAS II RA would be issued by their respective systems. ACAS Xu also builds upon TCAS II by issuing horizontal RAs in addition to vertical RAs. This capability results from the improved sensor performance with ACAS Xu relative to TCAS II equipment. Horizontal RAs are particularly appropriate for UAS since many UAS platforms have limited vertical-rate performance and relatively high turn performance. A consequence of ACAS Xu horizontal RAs is the potential for concurrent vertical and horizontal RAs, which is referred to as a "blended" RA and requires pilots to maneuver in both dimensions simultaneously.

The present work details a two-part, medium-fidelity, human-in-the-loop study that examines two research gaps pertaining to Class 3 systems (i.e., ACAS Xu). The first part of the study addresses the lack of research into the unique display, alerting and guidance requirements for Class 3 systems. Of particular interest is how to present horizontal and blended RAs visually and aurally, since they have not yet been assessed in a human-in-the-loop setting. The second part of the study investigates options for automating the execution of ACAS Xu RAs. The DAA MOPS provide manufacturers the option of automating the CA function for Class 2 and Class 3 systems as a way of mitigating response delays from remote pilots. The current study varies which aspects of the CA function are automated - executing the RA and/or executing the return-to-course (RTC) maneuver – and reports on pilots' impressions of the automation features and implementation.

II. Method

A. Participants

Five pilots were recruited for each part of this study, resulting in ten total participants. Part 1 participants were instrument flight rules (IFR) rated commercial and general aviation pilots (M = 52 years of age) with medium-to-expert level TCAS II experience, and an average of 173 unmanned and 7,180 manned flight hours. Part 2 participants were active duty United States Air Force (USAF) MQ-9 pilots (M = 29 years of age) with medium-level TCAS II experience and an average of 1,378 unmanned and 1,078 manned flight hours.

B. Simulation Environment

1. Ground Control Station

The ground control station in this study used the Air Force Research Laboratory's (AFRL) Vigilant Spirit Control Station (VSCS) [10] to simulate the flight of an MQ-9 Reaper. The configuration included a computer mouse, keyboard, and two monitor displays (Fig. 1). The main monitor display, referred to as the Tactical Situation Display (TSD), contained vehicle control interfaces and moving maps as well as DAA and RA alerting and guidance. A 'baseball card' that was centered on the top of the TSD provided information regarding present altitude, heading, indicated airspeed (IAS), vertical velocity, and an artificial horizon. The right monitor display presented navigation, telemetry, mission checklists, and a command chat message room. Participants operated the GCS in a secluded room. An experimenter served as a confederate Oakland Center air traffic controller (ATC). Pilots communicated with the ATC confederate through a push-to-talk headset.

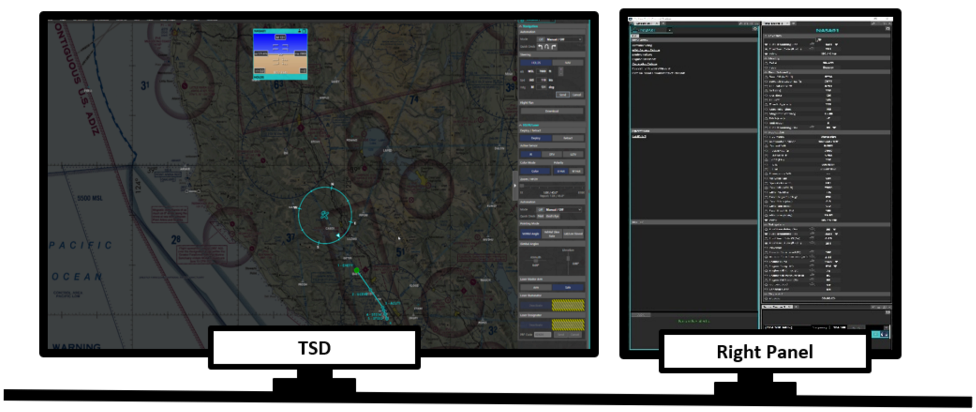


Fig. 1 GCS configuration.

2. DAA System

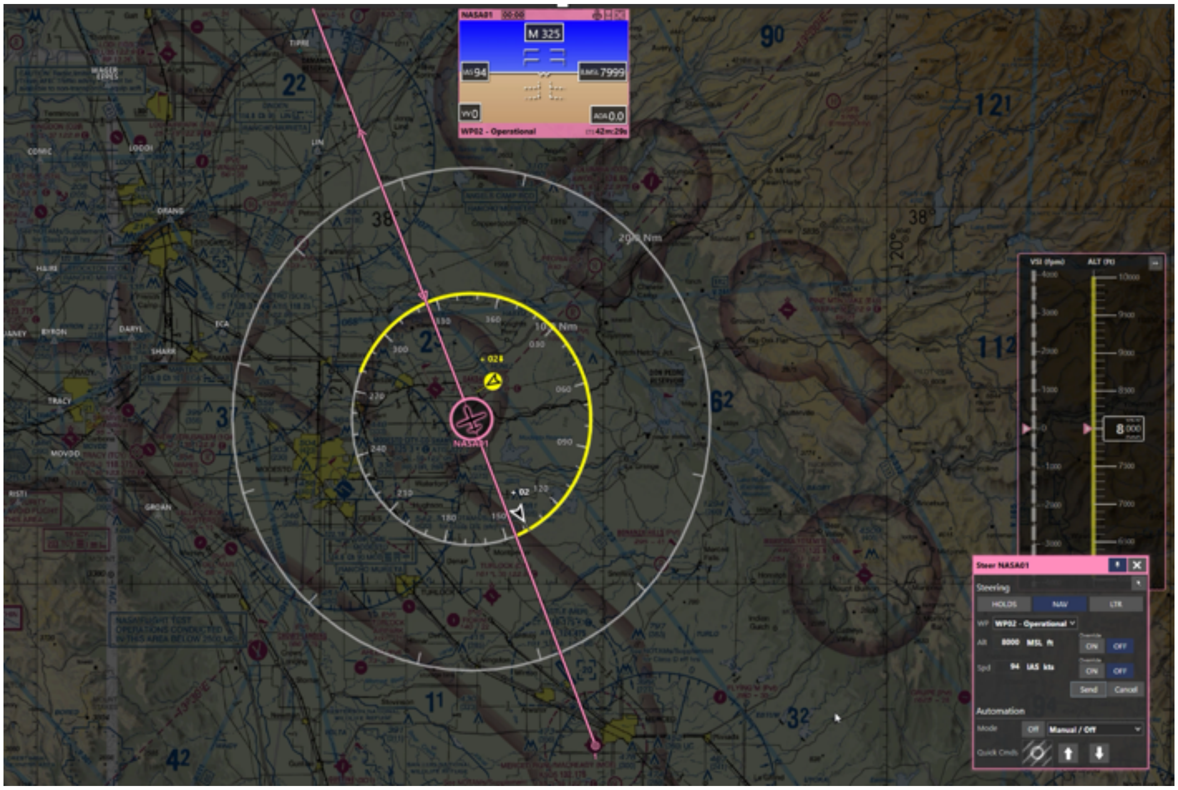
The current study did not incorporate the actual ACAS Xu logic into the simulation environment. Instead, the Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) was used to provide DAA information (i.e., visual alerts, maneuver guidance, and aural annunciations) up through the corrective alert level (see Table 1). Guidance traffic, preventive and corrective alerts, and corrective-level guidance were all generated nominally by DAIDALUS and displayed to the pilots in this study. Corrective-level guidance was configured to display the heading ranges and/or altitude ranges that were predicted to lead to a loss of DAA well clear on the TSD's inner range ring and altitude tape, respectively (see Fig. 2a). In order to mimic ACAS Xu, the alerting and guidance generated by DAIDALUS was suppressed starting at 5 seconds from a loss of DAA well clear, which is approximately the time at which ACAS Xu is expected to issue its Resolution Advisories relative to the DAA well clear boundary. At this point, VSCS displayed a pre-determined set of RA guidance to the pilot. This was preferable to the actual ACAS Xu logic since it was more controllable and repeatable. Only a subset of the possible ACAS Xu RA types were scripted to occur in the current simulation to limit the number of variations of the experimental design. The following RA types were scripted to occur in Parts 1 and 2 of the study:

- *Vertical-only RAs*. Vertical RAs provide the pilot with a target vertical speed range (nominally +/- 1000-1500 FPM). In this study vertical RAs were displayed as red ‘avoidance’ bands and green ‘fly-to’ bands on a vertical speed tape on the TSD. Vertical RA guidance was paired with RA aural annunciations (“Climb, Climb” or “Descend, Descend”). To prevent potentially contradictory guidance, the DAA guidance on the altitude tape (which was used to depict vertical corrective guidance bands) was suppressed during a vertical RA. This was depicted by grey, dashed banding on the altitude tape. Horizontal corrective bands continued to be displayed during the vertical RA. Since a loss of DAA well clear was considered unavoidable at the time of an RA and ACAS Xu does not issue warning-level guidance, all headings were associated with corrective-level banding. Vertical RA guidance, as presented during a Blended RA, can be seen on the right side of Fig. 2b.
- *Horizontal-only RAs.* Horizontal RAs provide the pilot with a target heading range. In this study, the target heading range was conveyed by a 10-degree green fly-to heading band on the inner range ring. A red avoidance band was depicted starting at the target heading and extending in the opposite direction to 180 degrees behind ownship’s current heading. Horizontal RA guidance was paired with RA aural annunciations (“Turn Left, Turn Left” or “Turn Right, Turn Right”). Vertical corrective bands continued to be displayed on the altitude tape during the horizontal RA. Since there was no active vertical RA, the vertical rate guidance was shown as suppressed (i.e., grey, dashed banding). Horizontal RA guidance, as presented during a Blended RA, can be seen in the center of Fig. 2b.
- *Blended RAs*. Blended RAs refer to concurrent vertical and horizontal RA guidance. In this study, blended RAs could be either ‘simultaneous’ (i.e., horizontal and vertical RAs initiated at the same time) or ‘offset’ (i.e., either the horizontal or vertical RA is issued first, with the opposing RA dimension added several seconds later). The visual RA guidance for vertical and horizontal RAs was depicted identically to how they were issued in isolation, with the exception that no corrective-level DAA guidance was presented during Blended RAs since both dimensions had active RA guidance. The aural annunciations for Blended RAs, however, were combined to indicate that both maneuvers were to be commanded and maintained for the duration of the blended RA. For instance, a ‘turn right’ horizontal RA and a ‘climb’ vertical RA was nominally presented as “Turn Right and Climb, Turn Right and Climb”. In a subset of the Part 1 conditions, additional logic was applied to modify how offset blended RA aural alerts were announced. This behavior is described in further detail below.

In half of the trials in Part 1 of the study, the RA alerting and guidance was supplemented with a text box (seen in the top right corner of Fig. 2b), detailing the type of RA and the target heading and/or vertical rate. In conditions that utilized automation in Part 2 of the study, a visual indicator would appear in the lower left-hand corner of the TSD informing the pilots that automation was enabled (see Fig. 3a and Fig. 3b). Upon automatic execution of the RA or RTC maneuver, an indicator would appear to the right of the baseball card informing the pilots that automation for either the RA or RTC response was engaged (Fig. 3a and Fig. 3b).

Table 1 ACAS Xu alerting structure.

Symbol	Name	Pilot Action	Aural Alert
	Resolution Advisory (RA)	• Immediate action required to comply with RA	“Climb/Descend” x2 “Turn Left/Right” x2 or a combination of above
	Corrective DAA Alert	• No action required • Nominally, action would be taken to remain well clear	“Traffic, Avoid”
	Preventive DAA Alert	• No action required • Possible increase in threat level	“Traffic, Monitor”
	Guidance Traffic	• No action required • Traffic generating guidance bands outside of current course	N/A
	Basic Traffic	• No action required • No coordination required	N/A



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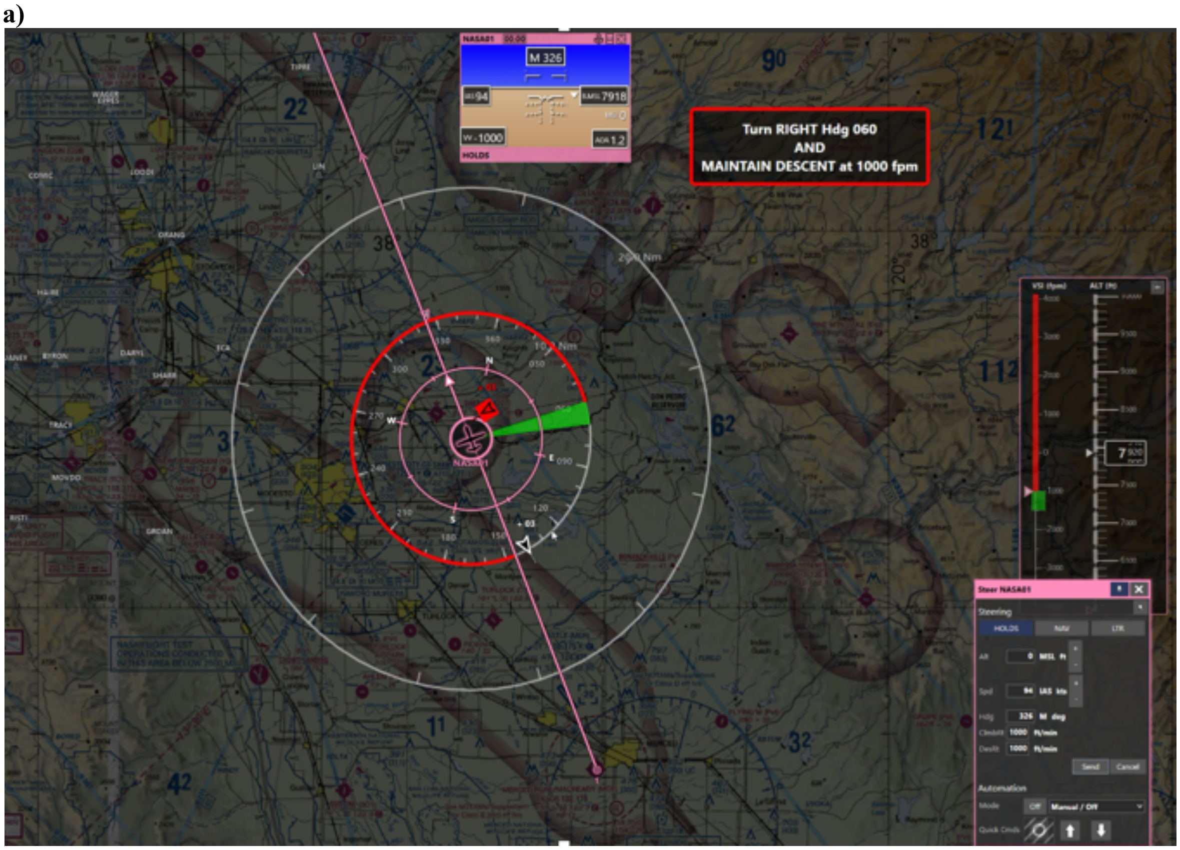
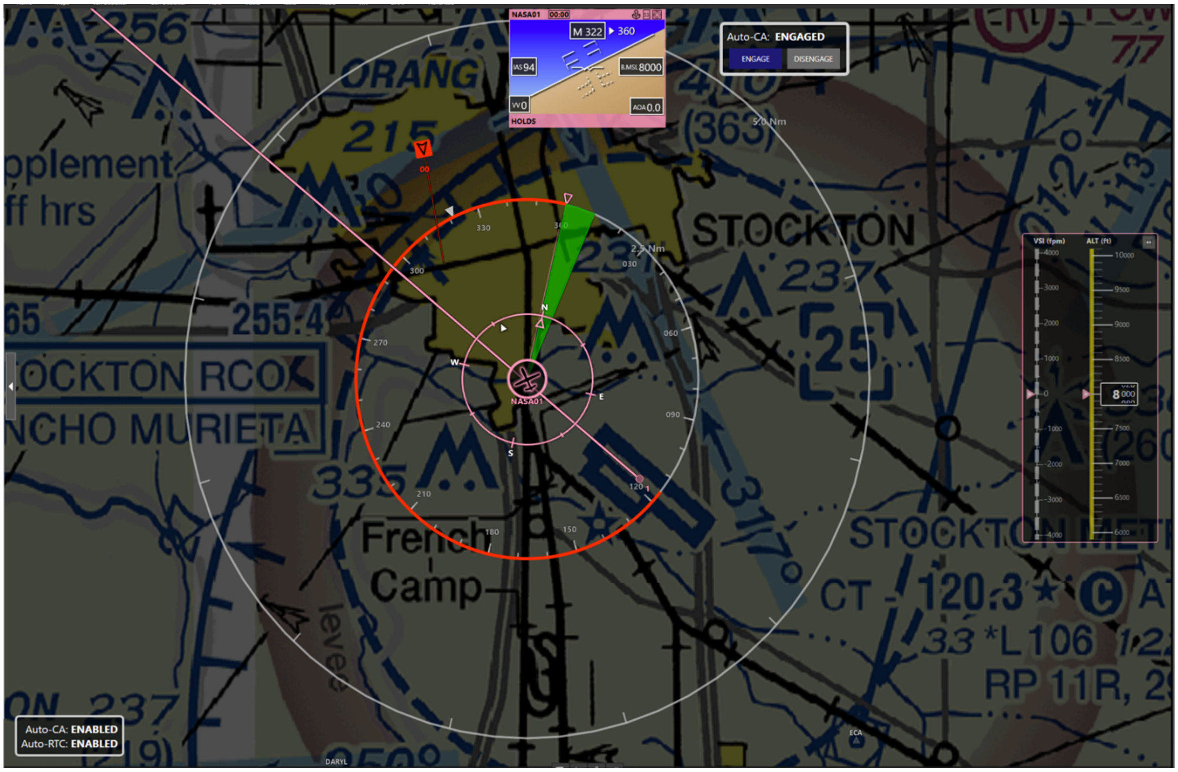


b)

Fig. 2 Examples of a) DAA corrective alert with corrective-level heading and altitude guidance, and b) ACAS Xu Blended RA guidance (vertical speed and heading guidance) with an RA text box (upper right).



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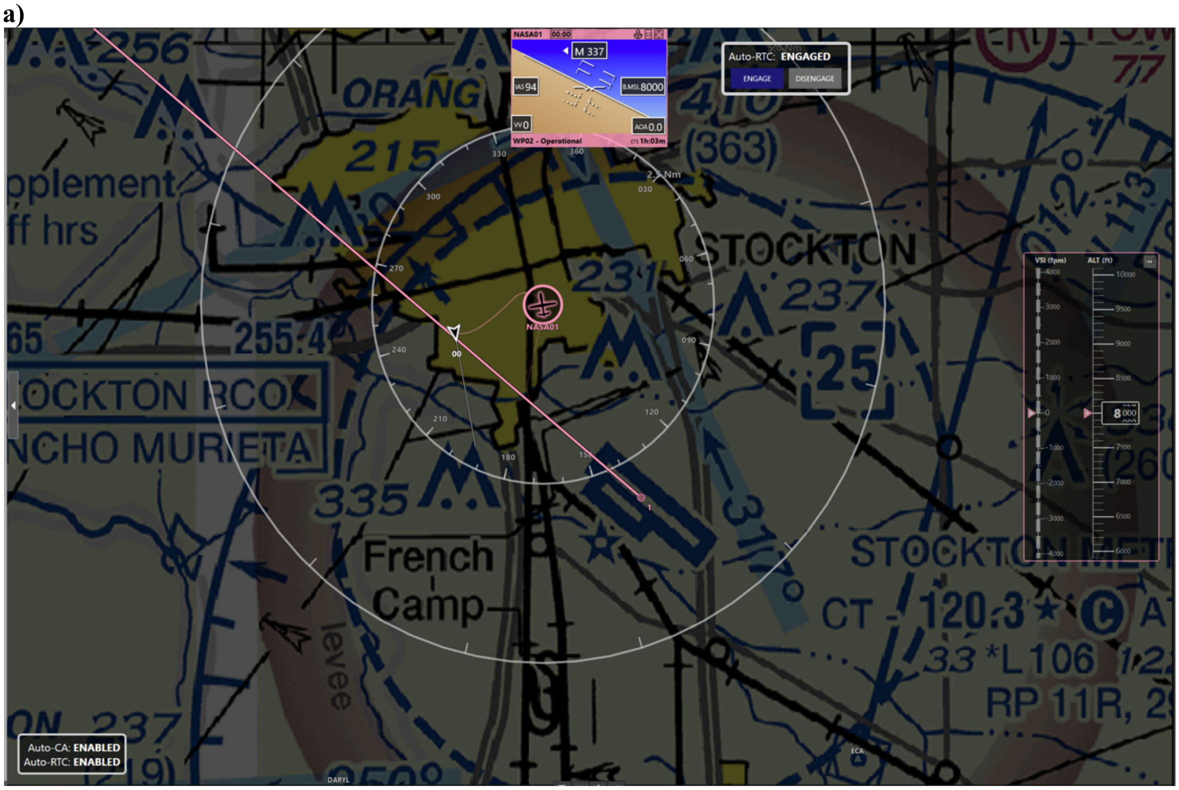


b)

Fig. 3 Examples of a) engagement of the automatic execution of a Horizontal RA, b) engagement of the automatic execution of RTC.

C. Experimental Design

1. Part 1

The present study was performed using a within-subjects design. Part 1 explored the effects of different display configurations on pilots' responses to different types of Resolution Advisories (RAs). This was accomplished using two independent variables (IV) with two levels each. The first variable manipulated whether a text box accompanied the RA visual and aural alerting and guidance. The "With-Text" condition included a text box that contained information about the RA (e.g., "Turn RIGHT Hdg 300"). The text box was positioned next to the baseball card in the top-right of TSD. No such text box was provided in the "No-Text" condition. This variable was included in order to explore whether the presence or absence of text guidance would increase the accuracy of compliance, as well as the compliance rate overall, particularly with the novel horizontal and blended ACAS Xu RA types. The second variable manipulated how offset blended RAs were announced. In the "Basic" condition, the aural alerts were issued nominally (e.g., "Turn Right and Climb, Turn Right and Climb") regardless of whether or not the vehicle had already achieved the target heading or vertical speed associated with the first RA at the time that the second RA was added. In the "Advanced" condition, a simple logic check was performed when the second RA was added to determine whether the target value had been achieved for the first RA. If it had been achieved, the blended RA aural alert would announce "maintain heading" or "maintain vertical speed" if the initial horizontal or vertical RA had already been reached, rather than repeat "turn left/right" or "climb/descend" announcement. The goal of the advanced condition was to more clearly indicate which dimension required additional action on the part of the pilot. A within-trial variable of RA type was also included. The RAs types were vertical-only, horizontal-only, blended-simultaneous (i.e., vertical and horizontal RAs provided at the same time), and blended-offset (i.e., vertical and horizontal RAs provided eight seconds apart).

2. Part 2

Part 2 explored the effect of automated maneuver avoidances and return-to-course maneuvers. Whereas auto-execution of vertical RAs has been put into operation in certain instances of TCAS II, there is a critical need to get data and feedback on the behavior of auto-CA and auto-RTC functionality in the context of the ACAS Xu. We examine this question by presenting increasing levels of automation (counterbalanced) to pilots in Part 2 in order to get direct feedback from UAS pilot participants. This was accomplished using four conditions: Manual, Auto-CA, Auto-CA & RTC, and Auto-CA & RTC+. The Manual condition required pilots to comply with RAs manually, similar to Part 1. The Auto-CA condition automatically and immediately commanded the target heading and/or vertical speed upon the initiations of RA(s). Auto-CA & RTC automated both the RA maneuver(s) and the execution of RTC once a Clear of Conflict (CoC) message was generated by DAIDALUS. Lastly, Auto-CA & RTC+ differed from Auto-CA & RTC by way of including additional aural alerts to indicate automation engagement. When the automation engaged the CA response, "Executing" was announced immediately following the standard RA annunciation. For example, if a 'turn left' horizontal RA was issued in the Auto-CA & RTC+ condition, pilots would hear "Turn Left, Turn Left; Executing". When the automation engaged the RTC response, "Returning" was immediately announced. Pilots had to take corrective action in order to disengage an active RA. This was accomplished by pressing a dedicated "Disengage" button. Upon pressing this button, the pilot regained the ability to modify the vehicle's heading during a horizontal RA and/or the ability to modify the vehicle's altitude during a vertical RA.

D. Procedure

1. Training

Upon completion of informed consent and demographic forms, pilots received both education and interactive training on the GCS and associated DAA system. Presentations introduced the participants to project-related history and context on the UAS integration into the NAS project, DAA, ACAS Xu, and VSCS. Participatory training allowed the pilots to practice controlling the GCS prior to data collection. Researchers utilized training checklists to verify proficiency as participants became familiar with the system. Pilots learned the system in stages, starting with basic ground station functionality, followed by training on the DAA alerting and guidance and associated RA alerting and guidance. In Part 2 of the study, the pilots were also trained on the automation behavior and where to find automation indicators in each of the conditions.

2. DAA Pilot Tasks

In both Parts 1 and 2, pilots were tasked with operating their aircraft along a preprogrammed flight path. No background traffic or secondary tasks were included in the experimental scenarios. Pilots were instructed to not respond to DAA alerting and guidance to prevent them from avoiding the RAs entirely. DAA alerting and guidance was still displayed to pilots, despite the instruction to not respond to it, so they could offer feedback on the transition from DAA guidance to RA guidance. Each pilot experienced four counterbalanced trials lasting approximately 45 minutes each. Ten types of encounters occurred during each trial; these included two no-threat encounters and two of each of the four RA encounter types: vertical-only, horizontal-only, blended-simultaneous, and blended-offset.

In all of Part 1 and in the Manual condition in Part 2, pilots were required to manually comply with the commanded RA for each given RA event. For vertical RAs, this was accomplished by selecting a climb or descent arrow within the TSD's 'steering window'. The arrow would input a 3000 foot climb or descent into the steering window (altitude maneuvers are made in VSCS via altitude commands, rather than solely by commanding a vertical rate) and the pilot would press "Send" to confirm and upload the maneuver to the vehicle. For horizontal RAs, manual compliance was achieved by the pilot clicking and dragging a graphical heading bug to a desired heading, or by manually typing in the desired heading into the steering window. Once the pilot was satisfied with the target heading, they pressed "Send" to upload the maneuver to the vehicle.

In the three automated conditions in Part 2, pilots were expected to monitor the vehicle and allow the automation to perform the auto-CA or auto-RTC response. Each trial in Part 2 was designed to have one encounter in which the automated remedial action failed. This meant that ACAS Xu would indicate that automation was engaged, however no maneuver(s) ensued. As a result, pilots were required to disengage the automation and manually upload the necessary maneuver. Without including the failure condition, it was likely that pilots would gain no experience with the automation disengagement process. Including it in the present study allowed experimenters to get direct feedback on that process.

E. Measures

Objective data was collected using output logs from VSCS, which captured pilot interactions with the vehicle control interfaces and recorded the times at which the RAs were issued. A screen recording of the TSD was also made for each trial so that researchers could review pilot interactions in their proper context. Subjective data was collected using post-trial and post-simulation questionnaires as well as debrief interviews.

1. Response Times

Pilot response times are collected using VSCS output logs and confirmed via a review of screen recordings of the TSD. The response time is measured as the time elapsed between the issuance of the RA and the pilot's successful upload of a maneuver in compliance with the RA. ACAS Xu has a response time requirement of 5 seconds to the initial RA in an encounter and 2.5 seconds to any subsequent RAs in an encounter. It is, therefore, critical to determine how well remote pilot response times conform to this requirement.

2. Compliance Rates

Compliance rates are the rate at which pilots commanded a heading and/or vertical speed that was in conformance with the target heading and/or vertical speed range (i.e., within the green fly-to bands) associated with a given RA. Pilots failed to comply if the heading or vertical speed range stayed within the red avoidance band regions over the course of an entire RA.

3. Subjective Data

Pilots filled out post-trial and post-simulation questionnaires in both Parts 1 and 2. The questionnaires in both parts focused on the acceptability of the various display components in each aspect of the test. Part 2 questionnaires also included questions regarding the viability of the automation configurations. A semi-structured debrief session followed the completion of the post-simulation questionnaire in both Part 1 and Part 2.

III. Results

We present the results from Parts 1 and 2 of this study in the sections that follow. Objective results (i.e., response times to, and compliance with, RAs) are the primary focus for Part 1 on this study. Conversely, results for Part 2 of the study consist primarily of subjective feedback from pilots given that responses to events were automated for three out of the four trials. The results from both parts of the experiment provide insight into potential system improvements, such as the presentation of RAs and automation behavior.

A. Part 1: RA Display and Alerting Results

1. Response Times

The primary driver of pilot response times (RTs) to RAs was the RA type — that is, whether the RA was vertical, horizontal, or both (i.e., blended). Figure 3 shows the average pilot response times to the three types of initial RAs presented in this study: horizontal-only, vertical-only, or blended-simultaneous. Pilots complied fastest to vertical-only RAs ($M = 4.52$ s, $SE = 0.29$ s) in comparison to other RA types (i.e., horizontal-only RAs: $M = 7.42$ s, $SE = 0.29$ s; blended-simultaneous RAs: $M = 9.68$ s, $SE = 0.74$ s). Notably, vertical-only RAs were the only RA type to result in a response time that fell within the 5-second response time requirement for initial RAs.

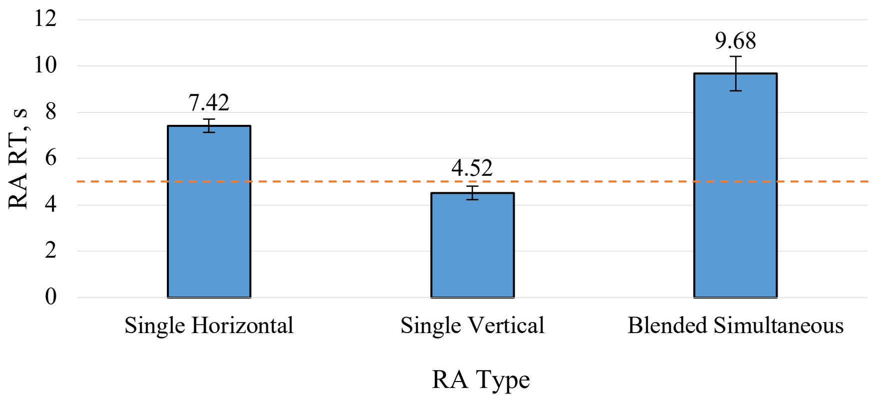


Fig. 3 Mean Response Times by RA Type.

Table 2 and Fig. 4 show pilot response times to the first and second RAs in blended offset RAs. Blended offset RAs in this study begin as a one-dimensional maneuver followed by a second dimension added 8 seconds after the initial RA. As shown in Fig. 4, pilot response times to horizontal and vertical RAs did not meaningfully change whether it was the first or second RA in the blended offset sequence. This breaks from the assumption that pilot response times to subsequent RAs will be faster than the response time to the initial RA. As with the initial RA response times, response times for horizontal maneuvers were on average ~2-3 seconds longer than vertical RTs when they were the second RAs in the sequence.

Table 2 Mean Response Times to Blended-Offset RAs.

		RA Order	
		Initial	Follow-On
RA Type	Horizontal	$M = 7.32$ s, $SE = 0.09$ s	$M = 7.05$ s, $SE = 0.49$ s
	Vertical	$M = 4.15$ s, $SE = 0.38$ s	$M = 4.82$ s, $SE = 0.65$ s

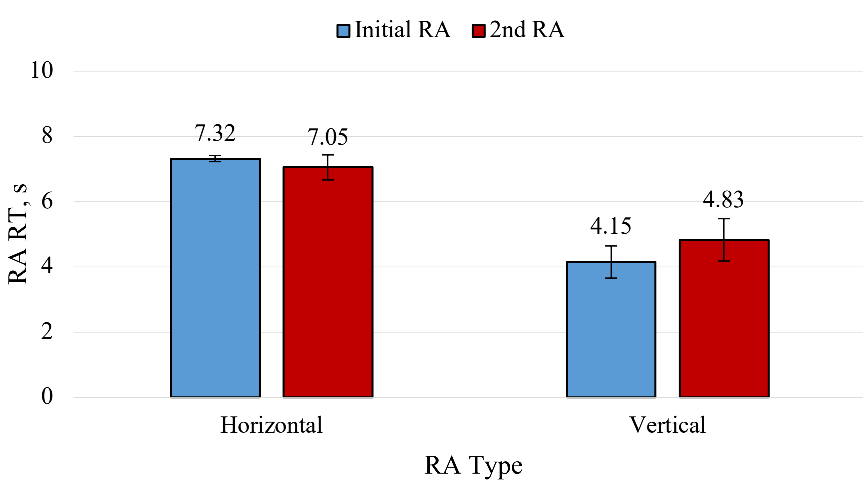


Fig. 4 Mean Response Times to Blended-Offset RAs.

The RA With-Text/No-Text and Basic/Advanced aural alert manipulations were not found to have any impact on pilot response times. As shown in Fig. 5, the With-Text/No-Text variable did not have a meaningful effect on pilot response times. Similarly, Fig. 6 shows that the Basic/Advanced RA aural alert manipulation did not impact pilot response times to the blended-offset RA type.

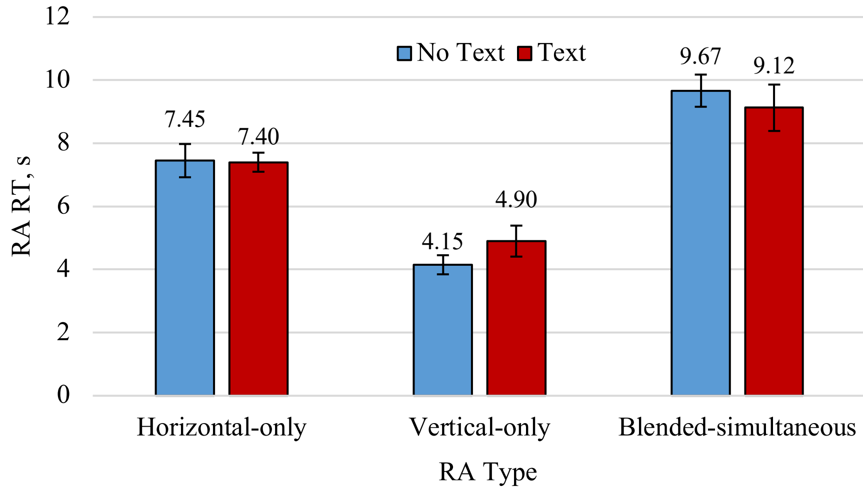


Fig. 5 Mean Response Times by RA Type and Text Condition.

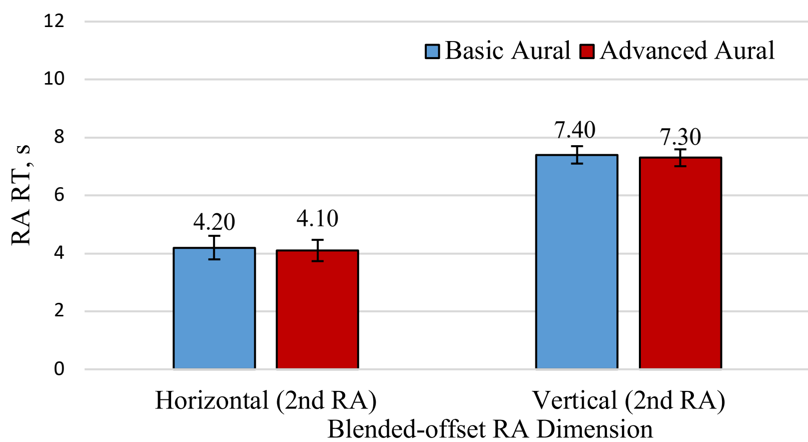


Fig. 6 Response times to the second RA in a blended offset RA sequence by aural alert condition.

2. Compliance Rate

Pilots in this study were found to have a perfect compliance rate for both horizontal and vertical RAs. This is to be expected given the simplicity of the task environment (no secondary tasks) and the lack of any legitimate reasons to not comply with any RAs in the study (e.g., a higher-priority warning system taking precedence). There was, however, one minor effect of the With-Text/No-Text manipulation on how pilots complied with horizontal RAs. As Fig. 7 shows, pilots were twice as likely to upload the exact RA target heading for horizontal RAs in the With Text condition. This is because the text box included the precise target heading value, while the green fly-to bands alone showed a 10-degree band region of acceptable headings. Regardless, pilots were extremely effective at either selecting the exact target heading or a target heading within the green band region. In one case, a pilot selected a heading that was greater than the 10-degree buffer on the target heading (i.e., an ‘overshoot’), but this was still considered conformance since the pilot kept the commanded heading outside of the avoidance band region.

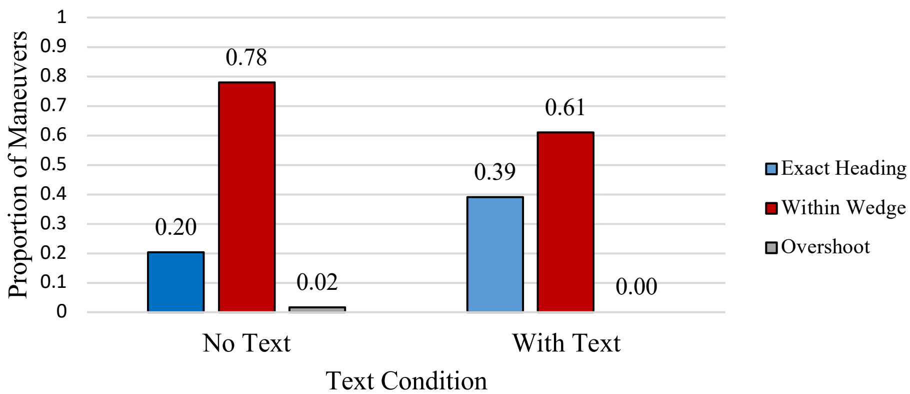


Fig. 7 Exact and "Within-Wedge" Horizontal RA Compliance Rates.

3. Subjective Feedback

Part 1 participants were asked whether they agreed with the statement, "Do you consider an RA text box necessary?", on a Likert scale of 1 (Strongly Disagree) to 5 (Strongly Agree). One of the five pilots reported to strongly agree, while the remaining four pilots were either neutral or disagreed. It should be noted, however, that the display configuration used in this study (where the RA information was collocated with the vehicle control interfaces) undoubtedly diminishes the utility of an RA text box. It is likely that different configurations will elicit different pilot responses to this question.

Pilots were also asked whether they preferred the Basic or the Advanced aural alert condition when responding to blended offset RAs. Four of the five pilots reported a preference for the Advanced aural alert compared to the Basic aural alert.

Finally, pilots were asked to rate the effectiveness of the visual guidance for horizontal and vertical RAs on a scale of 1 (Very Ineffective) to 5 (Very Effective). All five pilots rated the horizontal RA visual guidance as very effective, while three pilots rated the vertical RA visual guidance as very effective and the remaining two pilots rated it as effective.

4. Part 1 Summary

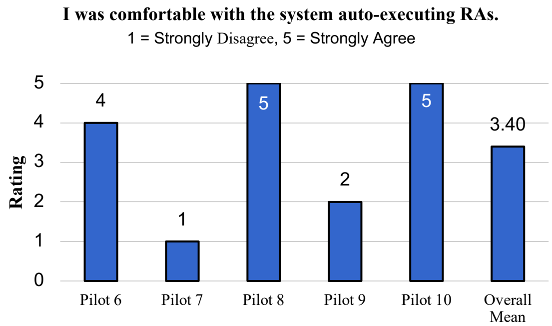
The above results demonstrate that the issued RA dimension is the largest determinant of RA response times. Responses to vertical RAs were far quicker than those for horizontal RAs. A substantial finding is that RTs for vertical RAs were the only type for which pilots, on average, could respond under the 5-second requirement. Response times for other RA types were above this limit: 7.5 seconds for horizontal RAs on average, while responses to blended-simultaneous RAs were substantially longer than the 5-second RT assumption at around 10 seconds on average.

The RA With-Text/No-Text and Basic/Advanced aural alerting manipulations were found to have no effect on response times. They did have a minor effect on compliance rates. When Text was provided pilots commanded two times as many exact horizontal maneuvers as opposed to the No-Text condition, though this is not a particularly meaningful result since pilots otherwise commanded maneuvers within the green fly-to wedge. The RA text and aural alert manipulations had the strongest impact on pilots' subjective ratings. Four of the five pilots found the text box information unnecessary, while four of the five pilots preferred the Advanced aural alert condition. More broadly, pilots found the presentation of the horizontal and vertical RA guidance to be very effective.

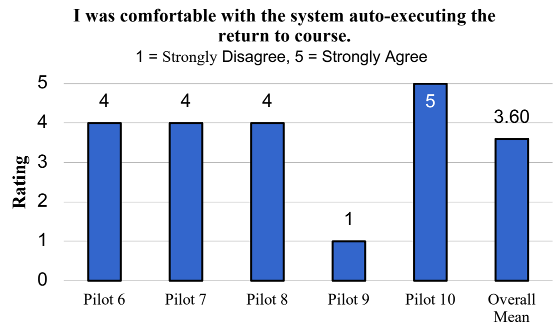
B. Part 2: Effects of Automation on Pilot Acceptance of ACAS Xu

1. Automation Utility

Pilots reported both automatic collision avoidance (i.e., auto-CA) and automatic return-to-course (i.e., auto-RTC) functionality to be useful. All five pilots who participated in Part 2 of the study provided positive responses regarding the usefulness of automating aspects of ACAS Xu during post-simulation debriefing interviews. Responses from pilots also indicated that pilots viewed auto-CA and auto-RTC functions to be about equally useful. As is evident in Fig. 8a, pilot comfort with auto-CA was either rated very highly or very low across participants. Automatic execution of RTC, on the contrary, was reported to have slightly greater overall comfort levels with only a single pilot providing a low rating (Fig. 8b). It should be noted that these ratings were after pilots had been exposed to one instance of the auto-CA function failing; one of eight auto-CA responses per trial were designed to fail intentionally.



a)



b)

Fig. 8 a) Pilot comfort with auto-execution of RAs, b) pilot comfort with auto-execution of RTC

2. Areas for Improvement

The bulk of the questionnaires and debrief, however, focused on identifying areas for improvement regarding automation behavior and how it was displayed to pilots in the study. As seen in Fig. 9, pilots were neutral in their responses to how clearly automation was engaged at any given time. Consequently, pilots were queried on how the displays could better support automation of the CA and RTC functions.

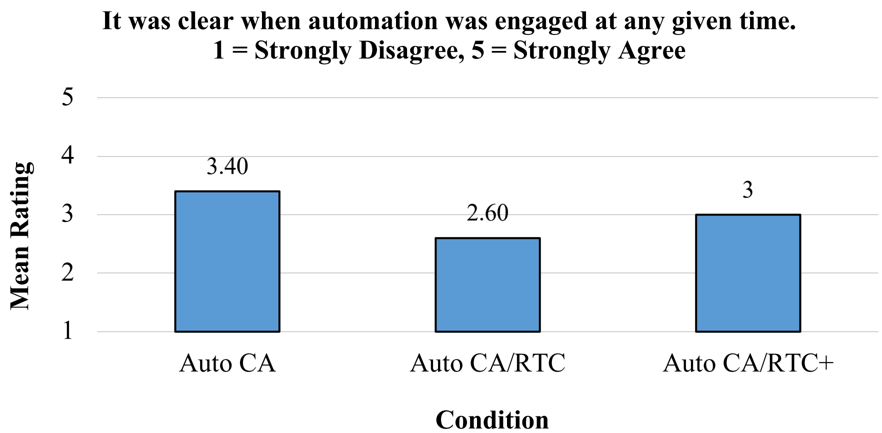


Fig. 9 Clarity of automation engagement by automation condition

All five pilots reported that the visual indicators for the engagement of auto-CA and auto-RTC could be improved. In both cases, pilots responded that the text boxes that indicated whether automation was or was not engaged needed more salience. Suggestions included flashing the status box, changing the color of the ownship icon and instrument panels to a grey scale when automation is engaged, and a more conspicuous location of the text box. Regarding the aural alerting, four of the five pilots in Part 2 rated the "executing" and "returning" verbiage that was utilized only in the Auto-CA & RTC+ condition as necessary. Some pilots did, however, recommend different language, such as using "maneuvering" instead of "executing" and "resuming" instead of "returning." Nonetheless, pilots were clear that a dedicated aural alert was useful to help improve awareness of when auto-CA or auto-RTC was engaging.

Pilots also indicated a preference for greater transparency to indicate an upcoming auto-RTC activation. Without knowing when RTC will activate, there is no ability to properly coordinate with ATC. This sentiment is reflected in the following quote offered by a pilot during debrief: "It's important for the pilot to be able to maintain control of the aircraft and talk to ATC, because it may not be safe to return if, for example, you had to climb or descend through a bunch of people's airspace." Overall, pilots ranked their preference of automation conditions (i.e., from most preferred to least preferred) as Auto-CA & RTC+ first, Auto-CA second, and Auto-CA & RTC last. The lack of the "returning" aural alert in the Auto-CA & RTC condition likely explains why that configuration was ranked last, whereas the presence of the aural alert in the Auto-CA & RTC+ condition likely explains why that configuration was ranked first.

Finally, feedback was provided on how the system should present failures or anomalies with automation. In our setup, the system provided no indication of an automation failure. Instead, it was the pilot's responsibility to notice that the automation had failed and that the aircraft was continuing along its original course. Three out of five pilots reported that an aural alert should announce that there was a failure or problem with the automation, rather than a failure that has no indication. In order to override the automation, pilots had to first click a 'disengage' button and then enter their avoidance maneuver. This two-step process was expressed to be too cumbersome when in an urgent situation such as an RA. Additionally, 3 out of 5 pilots wanted an aural alert to indicate that automation had been manually disengaged. The lack of a failure indication, in addition to the disengagement process, added roughly 6 seconds to the average initial response time (time between issuance of the RA and the pilot's first interaction with the vehicle controls) and roughly 8 seconds to the aircraft response time (time between issuance of the RA and the successful upload of the maneuver to the vehicle; see Fig. 10).

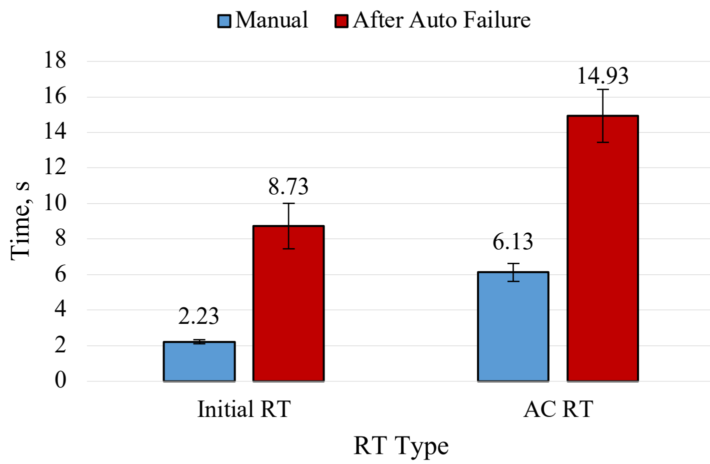


Fig. 10 Mean initial and aircraft response times to a nominal RA in the Manual condition and to an RA following failure of the automatic CA response.

IV. Conclusion

The objectives of this study were to address knowledge gaps relating to ACAS Xu. In particular, intentions for this study were to collect data to inform ACAS Xu RA display requirements as well as requirements should ACAS Xu collision avoidance functionality be automated. These two aspects of ACAS Xu—display requirements and automation requirements—were examined using a two-part approach; display configurations were examined in Part 1 of the study and automation requirements examined in Part 2. In this section, major findings of each part are presented followed by a discussion of next steps for ACAS research.

A. Part 1: ACAS Xu Display and Alerting Conclusions

The major findings of this portion of the study were that, in this best-case situation—i.e., no background traffic, participants expect encounters to occur, no coordination with ATC, and a low-workload environment, among other simplifications for experimental purposes—(1) vertical response times were the only RA type to fall within the 5-second response time requirement, (2) horizontal response times exceeded this threshold by ~2.5 seconds, (3) blended-simultaneous response times approximately doubled the requirement at an average response of ~10 seconds, and (4) compliance rates were 100%. Lastly, another ACAS Xu requirement is that, in cases where a follow-on RA is added to an initial-RA, the pilot is required to respond to the follow-on RA within 2.5 seconds. However, Part 1 pilots were no faster in responding to follow-on RAs than they were to single-vertical or single-horizontal RAs. These results can be attributed to the VSCS interface design. A response to a vertical RA only required one click on a continuous climb/descend button in the navigation pane, whereas the response to horizontal RAs required moving a heading bug to a particular heading or typing a heading value into the navigation pane before up-linking the maneuver to the aircraft. The response times observed in this study, therefore, were the fastest possible response times given the interface features for making vertical and horizontal maneuvers in VSCS. Pilots were unable to respond more quickly to horizontal RAs and to subsequent RAs because the interface could not support it.

Our display and alerting manipulations were found to have no effect on pilot RTs, with each combination producing a response time of about 6 seconds when collapsing across all RA types. Most pilots indicated that they would not consider text alerting to be a requirement. That said, this study biased pilot responses by virtue of having the RA alerting and guidance presented on the same display as the vehicle control interfaces. This allowed the pilots to directly reference the guidance as they manually entered their maneuver. In the event that the RA information was located separately from the vehicle control interfaces, pilots could very well benefit from having the RA information presented within a text box on the vehicle control display. Pilot responses to the blended-offset RA aural alerting variable were also consistent. Four of the five pilots preferred the "advanced" alert, which added logic to indicate whether or not the pilot had already achieved the target heading or vertical speed associated with the initial RA when the second RA was added. When the target had been achieved, the blended aural alert would first announce the new RA (e.g., "Turn Left," "Climb") and then would announce that the pilot should "maintain heading/vertical speed", rather than repeat the initial RA type. Pilots indicated that it was helpful to know that they did not need to maneuver any further in the initial RA dimension and could focus on maneuvering in the newly added axis. Regardless of the Text or Basic/Advanced aural display/alerting conditions, pilots rated the appearance of horizontal and vertical RA guidance (i.e., the red avoidance bands and green fly-to bands) as highly effective. This is an important finding since the display of horizontal and blended RAs has not yet been validated in a HITL setting.

Part 1 of this study demonstrated that the way in which the RA guidance was presented was highly effective according to pilot ratings. Crucially, it also demonstrated the effect of navigation control interfaces on the ability of ground pilots to meet the 5- and 2.5-second response times requirements. Pilots were able to meet the response times requirements for vertical RAs because the interface only required two button clicks. The horizontal RAs, however, required pilots to make multiple button clicks and either manually type in the desired heading or click-and-drag a graphical heading bug to the desired heading. Consequently, it would be constructive to study other GCS interfaces or input methods that could support compliance with response time requirements for initial and subsequent RAs.

B. Part 2: Automation Considerations for ACAS Xu

In Part 2 of the experiment, pilot feedback noted the utility of automating the CA and RTC functions while also pointing out ways to improve it. Pilots would have preferred greater visual salience when automation was engaged, perhaps by flashing the text box. Pilots noted that they preferred having an aural alert to indicate when automation was engaged, and also suggested alternative verbiage (e.g., "maneuvering" and "resuming"). Participants suggested that the automated RTC action be made more transparent by giving the pilot some awareness prior to activation (e.g., a countdown clock to when it will activate). This feature would allow pilots to better understand how the vehicle was going to return to route and would enable more effective communication with ATC.

Pilots also noted that they would have preferred a simpler automation disengagement process in the instances of automation failure. The two-step process that was implemented in this study, done to avoid inadvertent disengagements, was deemed to be too cumbersome in a time-critical situation like collision avoidance. While future designs could be implemented that do not require a two-step process, its benefits must be weighed against the potential for undesirable disengagements. Pilots noted that the automation failure conditions could have been further improved by issuing an aural alert when the system realized it was not responding to the RA automatically. The prolonged response times in the failure conditions further emphasize the need for a dedicated automation failure alert.

C. Limitations and Next Steps

Several limitations of this study are worth mentioning. First, the ground station interface required that pilots make inputs using a mouse and keyboard. While this is a standard method of interaction for many ground control stations, mouse-and-keyboard inputs are slow when compared to hands-on stick and throttle input controls, which allow pilots to immediately initiate a maneuver without having to first input a desired target heading or altitude. Any ground control station that intends to have a pilot manually respond to collision avoidance alerts (whether generated by TCAS II or ACAS Xu) using a mouse-and-keyboard must address this inherent limitation. Ideal solutions will limit the number of steps required to comply with an RA. One method implemented by the authors in a follow-on study was to automatically fill the target heading or target climb/descent into the auto-pilot interface. This meant that pilots only had to review the input information and click once to upload the maneuver. Other alternatives should be explored.

A second limitation in this study was the relatively small number of participants that were recruited for Parts 1 and 2, an artifact of a compacted schedule. The findings presented here must, therefore, be understood within the appropriate context, particularly as it regards the subjective feedback reported herein. Individual differences can have major impacts on the trends observed in subjective data. Additional data must be collected on the display of RA guidance and automation before conclusions can be definitive.

Finally, as noted, this engineering analysis utilized "canned" RAs to simulate those that would be issued by ACAS Xu. This was necessary because it is not possible to fully control which type of RA is issued (e.g., vertical-only, blended-offset, etc.) with the real ACAS Xu logic. Future work must also be performed with the actual ACAS Xu logic to derive more relevant conclusions about its performance. The authors have since conducted a follow-on human-in-the-loop study that utilized the genuine ACAS Xu logic. Data collection for this study was completed in June of 2019; objective and subjective results from that study will be presented in Refs. 13-14.

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