A Detect and Avoid System in the Context of Multiple-Unmanned Aircraft Systems Operations

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NASA's Unmanned Aircraft Systems Integration into the National Airspace System (UAS in the NAS) project examines the technical barriers associated with the operation of UAS in civil airspace. For UAS, the removal of the pilot from onboard the aircraft has eliminated the ability of the ground-based pilot in command (PIC) to use out-the-window visual information to make judgements about a potential threat of a loss of well clear with another aircraft. NASA's Phase 1 research supported the development of a Detect and Avoid (DAA) system that supports the ground-based pilot's ability to detect potential traffic conflicts and determine a resolution maneuver, but existing display/alerting requirements did not account for multiple UAS control (1:N). Demands for increased scalability of UAS in the NAS operations are expected to create a need for simultaneous control of UAs, and thus, a new DAA HMI design will likely be necessary. Previous research, however, has found performance degradations as the number of vehicles under operator control has increased. The purpose of the current human-in-the-loop (HITL) simulation was to examine the viability of 1:N operations with the Phase 1 DAA alerting and guidance. Sixteen UAS pilots flew three scenarios with varying number of UAs under their control (1:1, 1:3, 1:5). In addition to their supervisory and sensor mission responsibilities, pilots were to utilize the DAA system to remain DAA well clear (DWC) during scripted conflicts of mixed severity. Measured response times, separation performance, mission task data, and subjective feedback were collected to assess how the multi-UAS control configuration impacted pilots' ability to maintain DAA well clear and perform the mission tasks. Overall, the DAA system proved surprisingly adaptive to multi-UAS control for preventing losses of DAA well clear (LoDWC). The findings suggest that, while multi-UAS operators are able to maintain safe separation (DWC) from other traffic, their ability to efficiently perform missions drastically decreases with their number of controlled vehicles. Pilot feedback indicated that, for this context, the use of automation support tools for completing and managing mission tasks would be appropriate and desired, especially for ensuring efficient use of assets. Finally, human-machine interface (HMI) design considerations for multi-UAS operations are discussed.

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I. Nomenclature

HMD	=	Horizontal Miss Distance
modTau	=	modified Tau
s	=	seconds
ZTHR	=	vertical threshold

II. Introduction

There is increasing demand for Unmanned Aircraft Systems (UAS) to have routine access to the National Airspace System (NAS) for civil and commercial purposes [1]. Current-day policy compels pilots in the cockpit to 'see and avoid' surrounding aircraft in order to remain 'well clear' [2]. To maintain safety of flight with UAS integration into the NAS, detect-and-avoid (DAA) systems onboard UAS will be needed to aid remote pilots in effectively maintaining 'DAA well clear' (DWC) from intruder traffic from a ground control station (GCS). In 2018, RTCA Special Committee 228 published the first phase of the Minimum Operational Performance Standards (MOPS) for DAA systems [3]. The Phase 1 DAA MOPS include a separation criteria for DWC and the minimum display information set needed for timely conflict resolution. The DAA display, alerting, and guidance requirements have been a focus area for ongoing research. Previous studies have shown that including color-coded conflict alerting and suggestive maneuver recommendations along with intruder state information promote desirable pilot acceptability and performance with the DAA display [4-6]. Specifically, the alerting and guidance in the Phase 1 MOPS-compliant DAA system (detailed later) have reduced losses of DAA well clear (LoDWC) and minimized the severity of DWC violations that do occur in previous human-in-the-loop (HITL) simulations [7-13].

Phase 1 DAA MOPS assumed no more than one vehicle per pilot. In response to the US Office of the Secretary Defense's Roadmap for integrating UAS into the civil airspace [14], numerous studies have sought to "define appropriate conditions and requirements under which a single pilot can control multiple UAS simultaneously", and where performance bottlenecks occur. Studies have revealed that multi-UAS control (also referred to as 1:N control, where N is the number of vehicles the pilot controls) can considerably increase cognitive workload and decrease situation awareness for a single operator, due in large part to the disruptions that occur from switching between information sources [15-17]. It was shown in Ref. 18 that operators exhaust all of their working memory capacity while processing information from multiple sources, which led to sub-optimal use of the assets under their control.

Research has found that while increased levels of automation can mitigate the burdens of multi-UAS operations [19], there are cases where performance bottlenecks remain even with higher automation and interface improvements [20]. Automation has been shown to enable an operator's ability to fully control a single UAS for tasks related to the automation, though not others [21]. Higher levels of autonomy can lead to a loss of situation awareness and consequently result in poorer operator performance [22, 23], particularly in instances where automation is found to be unreliable [24]. Given that the simultaneous control of greater than one vehicle involves the working memory for multiple situations at once, Ref. 25 has proposed the use of sensor management aids for the support of rapidly gaining situation awareness when switching tasks and integrated system designs to reduced operator sensor and flight control inputs.

The present study expands on previous research investigating multi-UAS operations by including the DAA task as part of the remote pilot's responsibilities. Of particular interest is identifying potential changes to the Phase 1 DAA human-machine interface (HMI) standards that may be required in order to enable the simultaneous control of multiple medium-to-large UAS for transit operations. The current experiment also seeks to identify the circumstances in which automation would be especially beneficial to the pilot.

III. Method

A. Experimental Design

The present study utilized a within-subjects design to evaluate DAA and mission task performance under three pilot:UA control conditions: one operator controlling 1 UAS (1:1), one operator controlling 3 UAS (1:3), and one operator controlling 5 UAS (1:5). Counterbalanced run orders varied the number of UAS each pilot controlled between trials.

B. Participants

Fifteen active duty UAS pilots (*M* = 36 years of age) were recruited for the present study, with the majority of their flight experience being in military operations. Pilots had an average of 1,701 hours of unmanned flight experience and 1,292 hours of manned flight experience. A retired air traffic controller (ATC) and two general aviation pilots participated as confederates, managing all the background traffic in the experimental sector.

C. Simulation Environment

1. Ground Control Station

The Vigilant Spirit Control Station (VSCS), developed by the Air Force Research Laboratory (AFRL), served as the GCS utilized for this study [26]. The display configuration consisted of three key components over separate monitors. The Tactical Situation Display (TSD) as the primary display containing the ownship mission route(s), intruder traffic information (e.g., relative altitude, 30-second predictor line, vertical trend), and DAA alerting and maneuver guidance over a moving map. The top of the TSD contained a 'baseball card' for each unmanned asset (UA) under control. The ever-present baseball card included current and commanded aircraft states, a traffic banner with active alert status, and DAA maneuver guidance for nearby headings and altitudes (Fig. 1). The monitor above the TSD contained the out-the-window, synthetic terrain heads-up display (HUD) that pilots used to complete sensor tasks (detailed below). The monitor to the right of the TSD contained the electronic mission checklists, a tote board with aircraft state information, and a chat window where pilots responded to scripted messages that probed their situation awareness throughout each scenario. The control interface enabled heading and altitude inputs which could be executed via the graphical click-and-drag or keypad inputs to a 'steering window'. Altitude could also be manipulated by clicking on up/down arrows (or "spinners") that would increase/decrease altitudes in 500-foot (ft.) increments. Pilots uploaded commands to the aircraft by clicking the "Send" button located within the steering window. Conflicts scripted to lose DWC were engaged by researchers in a separate room using the Vigilant Spirit Simulation (VS Sim) software. Multi-Aircraft Control System (MACS) software generated background traffic designed to emulate a busy day in Oakland Center airspace (ZOA 40/41), as informed by a retired center ATC serving as a subject matter expert. The GCS employed a generic MQ-9 Reaper model, with each UA under participant control operating at level altitudes ranging from 5,000 to 12,000 ft.

2. DAA System

The multi-level alerting structure and DAA guidance seen in this study was generated by Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS; [27]). The DAA alerting and guidance was configured to alert each ownship aircraft to potential violations of the DWC threshold (as defined in Table 1). All surrounding traffic within 5000ft of ownship were displayed on the TSD, with a sensor range filter applied based on their equipage. For example, ADS-B equipage had a sensor range of 15 nautical miles (nm) and RADAR had only 8 nm detection.. The color-coded symbology was applied to all intruder traffic within sensor range and indicated threat severity, which was based on whether pilot action was required to remain DWC. Any increase in intruder threat severity was accompanied by an updated aural alert. Only the two most severe threat levels required eventual pilot action. The yellow Corrective alert indicated a caution-level DAA threat that requires corrective action to avoid a LoDWC, but allowed enough time for pilots to notify ATC of their intentions. The red Warning alert indicated a warning-level DAA threat that required immediate action to avoid a LoDWC, with ATC coordination following soon thereafter.

The DAA maneuver guidance provided pilots with conflict resolution bands that probed surrounding headings and altitudes for predicted threat status. The horizontal bands appeared on the inner range ring of the moving map. The vertical bands, located on the altitude tape to the right of the TSD, probed altitudes within ±3,000 ft. of ownship. DAIDALUS constantly updated the maneuver guidance bands to reflect the most current trajectories, and did not account for ownship or intruder intent. The heading and altitude bands were color-coded in correspondence with the predicted threat level from the alerting structure. Headings and altitudes with yellow bands were predicted to lead to a loss of DWC with an intruder aircraft within 25–55sec. Red banding indicated that a particular heading or altitude would lead to a loss of DWC within 25sec or less. Thus, regions with yellow or red banding were to be avoided, as maneuvers toward these areas would trigger at least one Corrective or Warning alert, respectively. Safe flight regions that would remain well clear with intruders were indicated by the absence of banding. In the event that resolution options for remaining DWC were no longer achievable, or a LoDWC had already occurred, the bands would fully saturate to red and present regain DWC guidance designed to maximize separation at closest point of approach (CPA) [28]. Pilots could only see DAA information for traffic within surveillance range of the UA they were currently focused on. Any unfocused ownship aircraft that flew within surveillance range of the focused ownship appeared as intruder traffic on the TSD. Alerting symbology was only shown from the perspective of the focused UA; pilots were required to manually switch their focus to the relevant UA any time they wanted to view its associated DAA alerting.

Table 1. Phase 1 DAA MOPS alerting logic.

Icon	Alert Level	Expected Pilot Response	DAA Well Clear Criteria	Time to Loss of DAA Well Clear	Aural Alert Verbiage
	Warning Alert	Maneuver immediately	HMD = 0.66 nm ZTHR = 450 ft modTau = 35 sec	25 sec	"Traffic, Maneuver Now" x2
	Corrective Alert	Maneuver following ATC approval	HMD = 0.66 nm ZTHR = 450 ft modTau = 35 sec	55 sec	"Traffic, Avoid"
	Preventive Alert	Monitor traffic; maneuver not currently required	HMD = 0.66-1.0 nm ZTHR = 450-700 ft modTau = 35 sec	N/A	"Traffic, Monitor"
	Guidance Traffic	No maneuver required	Associated with banding outside current course	N/A	N/A
	Remaining Traffic	No maneuver required	Within surveillance field of regard	N/A	N/A

D. Procedures

1. *Training*

After completing demographics and informed consent forms, pilots were briefed on general broad project objectives and the run schedule for that day. Pilots were then given hands-on training with the VSCS interface, followed by a practice trial to demonstrate proficiency with the DAA system and their mission responsibilities until comfortable to proceed. The practice scenarios took place before each 40-minute experimental trial to ensure familiarity with each control condition (1:1, 1:3, and 1:5). In order to move on to the experimental run, the participant had to successfully resolve multiple conflicts and complete multiple missions. The process was repeated until pilots completed three experimental scenarios - one under each pilot-UA configuration. The order of control condition was counterbalanced between participants. The primary pilot responsibility under all control conditions was to maintain DWC (safety of flight) while complying with mission checklists and airspace restrictions, including sector boundaries and a no-fly zone (5 nm radius) surrounding Sonoma County Airport (KSTS) in the lower quadrant of the sector.

2. *DAA Tasks*

Each scenario contained six scripted DAA conflicts predicted to lose DWC absent any corrective action from the test pilot. The nature of the conflicts varied across a number of variables embedded within each scenario: First Alert Type (Corrective or Warning), Focus (conflict against a Focused or Unfocused asset), and Event Type (Single or Multi-threat). In the single-UAS configuration, pilots were to respond to four Corrective alerts and two Warning alerts. This was also the case in the multi-UAS configurations, except half of the DAA threats conflicted against unfocused aircraft. For unfocused conflicts, pilots did hear the aural alert (see Table 1) and saw the current alert status in the traffic banner below that ownship's baseball card (Fig. 1). Pilots had to click the traffic banner or the baseball card itself to re-focus their traffic display to the ownship in conflict in order to access that aircraft's steering interface and input an avoidance maneuver. As shown in Fig. 1, the baseball card of the focused ownship was larger than the rest. Also unique to the multi-UAS scenarios was a multi-intruder event that involved two simultaneous Corrective alerts – one against a focused UA and one against an unfocused UA (Fig. 1).

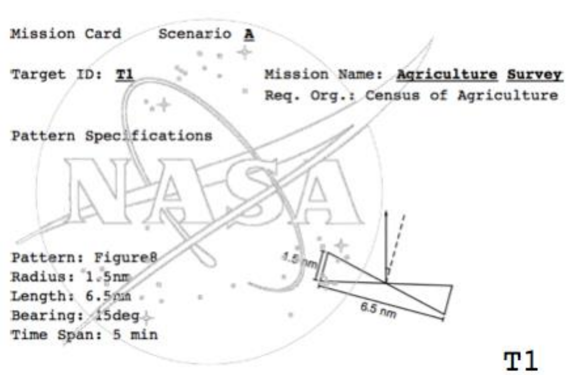
3. *Mission Tasks*

Each scenario launched with the ownship UA(s) loitering over designated starting points ('safe zones'). Target areas of interest (AOIs) for supervisory missions were displayed as flags across the TSD, all equidistant from the starting location(s) and one another. There were 18 mission flags to choose from, and pilots were given the freedom to decide the order in which they were targeted. Each mission flag had a label that corresponded to an electronic mission checklist (e.g., 'T1'). Pilots were instructed to complete as many missions as possible in the allotted 40 minutes, while complying with the mission checklists. Strategies for managing UAs and missions were up to the individual pilot, though all were asked to coordinate with air traffic control when changing areas of interest or maneuvering for traffic. In the event that every mission was completed during the scenario (technically only possible with 5 UAS), pilots were to send their UAs to their original safe zones with an indefinite loiter pattern until a researcher ended the run.

Fig. 1 A view of the baseball cards in the 1:3 control condition during a multi-threat event. Active DAA alert status and maneuver guidance are visible as part of the baseball card of the focused (middle) and unfocused UA (right). The stopwatch (top) was used to manually track time on task during supervisory missions.

Supervisory missions involved navigating the ownship aircraft to the AOI and maintaining a continuous orbit with the appropriate loiter pattern specifications for the assigned amount of time (example in Fig. 2a**)**. Once on target, the UA was required to loiter over the area of interest for four or five minutes. It was the pilot's responsibility to monitor the time on target and manage their transitions between missions. The stopwatch loiter timer within each baseball card (controlled via button-click) was the primary method of tracking the time spent on each task, and it was manually started once the UA entered the pattern. After maintaining the loiter for the requisite period of time, the pilots were free to send the vehicle to the next area of interest. In addition to the electronic checklists, pilots were provided with paper mission cards that detailed the loiter pattern specifications and simulated task associated with each AOI on the map. Pilots were trained to complete the electronic checklists during the scenario, while use of the paper mission cards were considered an optional, secondary reference. The final checklist item prompted pilots to mark the mission as complete on the TSD by changing the AOI flag to an 'X' icon using a drop-down menu. This was intended to help prevent duplicate efforts and track pilots' progress. Chat messages were periodically sent to pilots asking to report the number of missions they had completed to that point in the scenario.

There were also two sensor tasks that pilots were responsible for in each scenario. Sensor tasks were considered higher-priority, and were only prompted by scripted chat commands that occurred 10 and 25 minutes into each scenario. Pilots did not know when a given sensor surveillance task was going to be issued and were expected to transition to the one vehicle in their fleet with the video sensor payload to the designated area as soon as practical. Once entering the loiter pattern over the AOI, they had to monitor simulated sensor video on the HUD to search and acquire targets of interest, take a photograph of the target once acquired (example in Fig. 2b), and complete the appropriate electronic checklist. Targets of interest for sensor missions included: Cattle Survey, Downed Aircraft, Fire Monitoring, or Traffic Accident. The AOI location and nature of the sensor tasks were not made known before the scripted prompts, but they were always located in the upper quadrant of the sector near the launch point of the only camera-equipped UA. Sensor mission checklists also required an additional speed increase while en route to the AOI to indicate a heightened sense of urgency. Pilots did not encounter any DAA conflicts during an active sensor task, but were still responsible for monitoring time on task for the concurrent supervisory missions (if applicable). After complying with the sensor mission checklist, the pilot would inform 'Mission Control' in the chat window and proceed with their remaining supervisory tasks.



(a)

(b)

Fig. 2 Example of supervisory mission card and camera feed during traffic accident sensor mission.

IV. Measures

A. DAA Task Performance

1. Aircraft Response Time (Aircraft RT)

Refers to the elapsed time, in seconds, from the onset of a Corrective or Warning alert to the first avoidance maneuver uploaded to the vehicle.

2. Losses of DAA Well Clear (LoDWC)

Refers to the percentage of conflicts that penetrated the DWC threshold in each display condition, as well as the reason behind each LoDWC instance.

B. Mission Task Performance

1. Time Off Course

Refers to the amount of time in seconds pilots took to upload their return to the operational flight path after deviating for conflict avoidance.

2. Extra Time on Task

Refers to the amount of seconds that UAS spent in orbit past the minimum assigned loiter time for each supervisory mission.

3. Number of Missions Completed

Refers to the average number of supervisory missions completed under each UAS configuration.

V. Results

One-way repeated measures Analyses of Variance (ANOVAs) were conducted to analyze the impact of pilot:UA Control Condition (1:N) on the Aircraft RT, Time Off Course, and Extra Time on Task metrics, utilizing an alpha-level of 0.05. Descriptive statistics are reported for the LoDWC and Number of Missions Completed metrics.

A. DAA Task Performance

1. *Aircraft Response Time*

Overall, there was a main effect of Control Condition on Aircraft RT, which revealed faster responses with 1 UAS under control (M = 12.14*s*, SE = 0.65*s*) compared to 3 UAS (M = 15.01*s*, SE = 0.42*s*) and 5 UAS (M = 15.24*s*, SE = 0.76*s*), $F(2, 28) = 9.15$, $p < .05$. However, the significance of this result was modified by interaction effects found between two embedded variables: Event Type and Focus, $F(1, 14) = 10.67$, $p < .05$ First, there was a main effect of Event Type on Aircraft RT, which revealed faster responses to single-threat conflicts (M = 13.40*s*, SE = 0.53*s*) compared to multi-threat conflicts (M = 22.88*s*, SE = 1.11*s*), $F(1, 14) = 67.05$, $p < .05$. There was also an overall main effect of Focus found on Aircraft RT, where pilots responded faster to Focused conflicts (M = 13.31*s*, SE = 0.67*s*) compared to Unfocused conflicts (M = 18.92*s*, SE = 0.78*s*), $F(1,14) = 27.43$, $p < .05$. Pairwise comparisons revealed that the significant main effect of Focus only applied to multi-threat events, where pilots were alerted to a focused and unfocused conflict simultaneously (Fig. 3). Since conflicts against focused assets were usually treated as the primary threat and resolved first, RTs for Unfocused conflicts were nearly doubled when it was the secondary threat (M = 29.88*s*, SE = 2.34*s*) as opposed to the only (single) threat (M = 15.05*s*, SE = 0.86*s*). This appears to be the driving force behind major differences in Aircraft RT, as no main effect of Focus was found when controlling only for single-threat events, $p > .05$. It is important to note that the significant Aircraft RT increase associated with the secondary, unfocused conflicts was only reflected in the grand means for the multi-UAS configurations in which all multi-threat events occurred. Therefore, subsequent analyses sought to further isolate the effects of Control Condition on Aircraft RT by accounting for this disproportionate impact of Event Type. The aforementioned differences in Aircraft RT between the single-UAS and multi-UAS configurations indeed stabilized once controlling only for single-threat events (i.e., those that appeared in every condition), and no main effect of Control Condition on Aircraft RT was observed, $p > .05$.

Lastly, there was a main effect of First Alert Type on Aircraft RT, where pilots responded to Warning alerts (M = 9.99*s*, SE = 0.31*s*) significantly faster than Corrective alerts (M = 18.27*s*, SE = 0.80*s*), $F(1,14) = 87.14$, $p<.05$. This remained the case for each control condition, and the number of UAs did not significantly impact responses to Corrective and Warning alerts (Fig. 4). Although Corrective RTs were also extended (to a lesser extent) during multi-threat events, no significant interactions with any other variables were found.

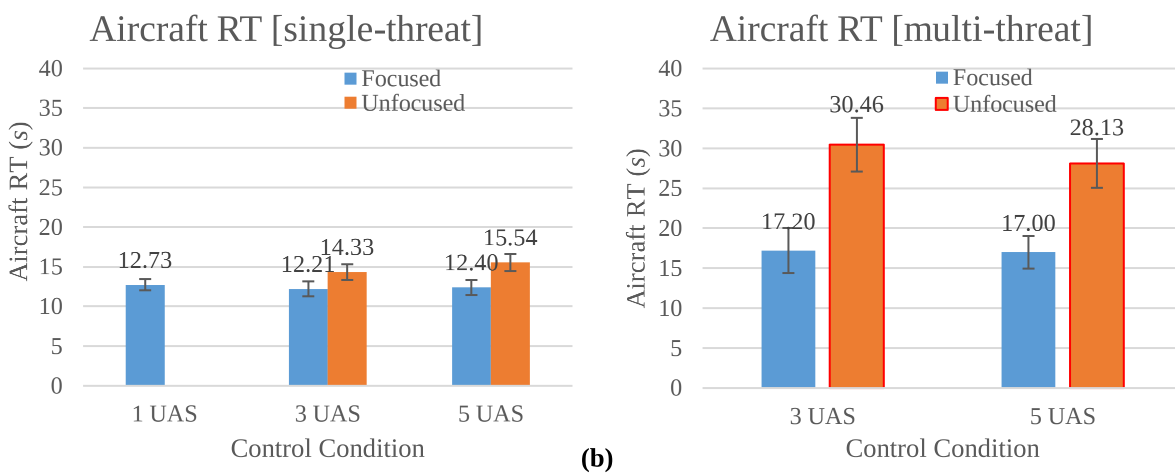


Fig. 3 Mean Aircraft RT by Control Condition & Focus for each Event Type (single and multi-threat).

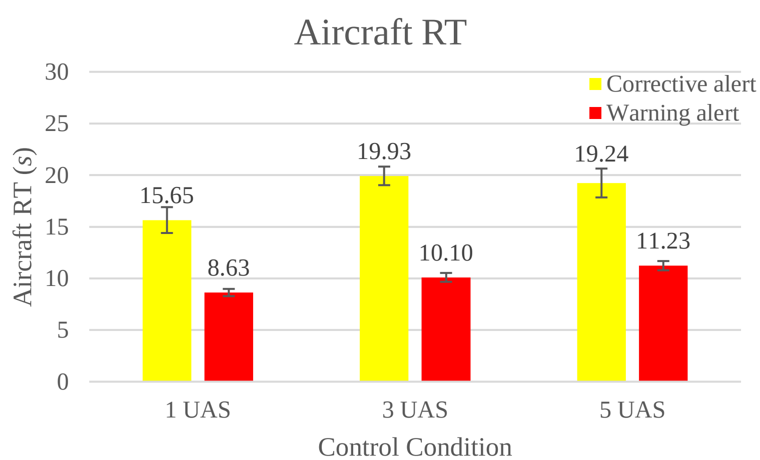


Fig. 4 Mean Aircraft RT by Control Condition & First Alert Type.

2. *Losses of DAA Well Clear*

Pilots avoided a LoDWC with 99% of the scripted conflicts over the entire study (N = 265). The highest LoDWC proportion was observed in the 5 UAS configuration (2.1%), followed by the 3 UAS configuration (1%). There were zero instances of LoDWC in the single UAS condition (Table 2). A warning-level conflict in the 5 UAS configuration was the only LoDWC event attributable to untimely pilot response. The other two LoDWC events involved pilots returning to course too soon after the conflict had been resolved, in an attempt to minimize path deviation.

Table 2. Proportion of LoDWC by Control Condition.

1 UAS	3 UAS	5 UAS
0/86 (**0%**)	1/90 (**1.1%**)	2/89 (**2.2%**)

B. Mission Task Performance

1. *Time Off Course*

There was a main effect of Control Condition on Time Off Course, $F(2, 28) = 6.34$, $p<.05$. Pilots spent less Time Off Course in the 1 UAS configuration (M = 45.91*s*, SE = 2.77*s*) compared to the 3 UAS (M = 60.34*s*, SE = 2.60*s*) & 5 UAS (M = 70.14*s*, SE = 8.37*s*) configurations (Fig. 5). No significant differences in Time Off Course were found between the 3 UAS and 5 UAS configurations, $p > .05$.

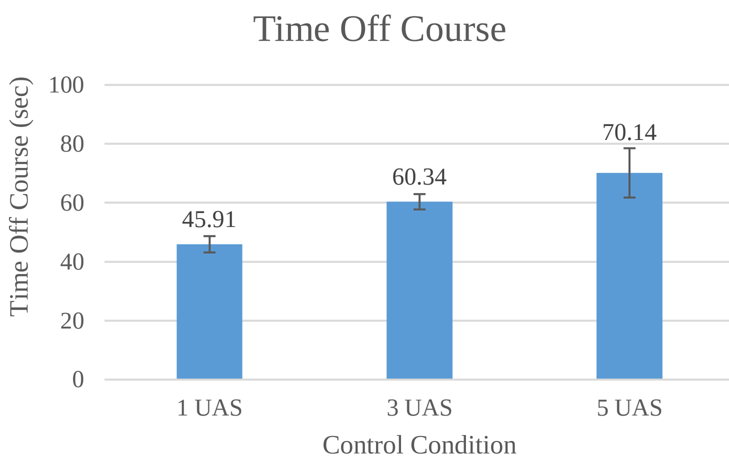


Fig. 5 Mean Time Off Course by Control Condition

2. *Extra Time on Task*

There was a main effect of Control Condition on Extra Time on Task: pilots spent less Extra Time on Task in the 1 UAS configuration (M = 16.11*s*, SE= 3.25*s*) compared to the 3 UAS (M = 76.04*s*, SE = 13.31*s*) and 5 UAS (M = 213.57*s*, SE = 33.03*s*) configurations, $F(2,28) = 31.82$, $p < .05$. The difference in Extra Time on Task between the 3 UAS and 5 UAS configurations was found to be significant, $p < .05$.

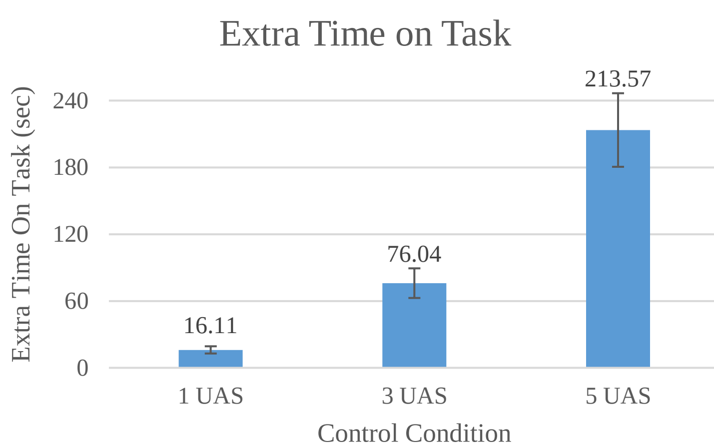


Fig. 6 Mean Extra Time On Task by Control Condition

3. *Number of Missions Completed*

On average, pilots completed a higher number of supervisory missions per scenario with 5 UAS (M = 12.69) compared to 3 UAS (M = 9.31) and 1 UAS (M = 2.94).

Table 3. Average Number of Missions Completed by Control Condition.

1 UAS	3 UAS	5 UAS
2.94	9.31	12.69

VI. Discussion

A. DAA Task Performance

The goal of the present study was to evaluate pilot performance with a DAA system integrated into a multi-UAS control environment. Overall, the results suggest the Phase 1 DAA system conformed favorably to the multi-UAS operations simulated in this study. DAA Task performance was comparable to past DAA studies that implemented the single-UAS configuration. The number of UAs pilots controlled did not have a significant impact on pilots' ability to effectively respond to DAA alerts in a timely manner. The slower Aircraft RTs in the multi-UAS conditions can most likely be attributed to conflicts against 'unfocused' ownship aircraft, which forced pilots to shift control from one UA to another. Although pilots in the multi-UAS conditions heard the aural alert and had DAA information available in the baseball cards for each aircraft under their control, they still had to switch the TSD's focus onto the conflicted asset in order to see the appropriate threat symbology and respond to it. Re-focusing to a different aircraft for conflict resolution extended initial pilot responses to DAA alerts by approximately 2-3 seconds, but this did not significantly impact RTs as a whole. However, during multi-intruder events with simultaneous caution-level threats against multiple ownships, pilots were significantly slower to respond to the unfocused threat than the focused – likely due to pilots consistently finishing their aircraft response to the focused threat first. There were times when the participant was not aware of the secondary threat until it elevated to a Warning alert, thereby triggering another aural alert. Luckily, the timing threshold for the DAA Warning alert has shown to be adequate for timely response, and this remained the case when having to manage multiple UAs. The DAA alerting and guidance was rated as well-understood, though pilots reported a desire for more distinct aural alerts for multi-threat encounters.

Aircraft RTs were nearly identical to the those obtained in previous, single UAS control research [10]. Average Aircraft RTs in Ref. 10 were 18 seconds to Corrective alerts and 10 seconds to Warning alerts. In the present study, the Aircraft RTs in the 1:5 condition were 19 seconds to Corrective alerts and 11 seconds to Warning alerts. The 5 UAS condition accounted for the only instance of LoDWC where the initial maneuver was not made in time to remain DWC, but still yielded LoDWC rates comparable to past 1:1 research [10]. The previous research had a global LoDWC proportion of 1%. The highest proportion of LoDWC in the present study was 2% (1:5 condition), followed by 1% (1:3 condition) and 0% (1:1 condition), a strong indication that pilots were able to manage DAA conflicts using the Phase 1 DAA system under multi-UAS operations.

Subjective feedback indicated that pilots were comfortable with the DAA alerting and guidance performance, and they were able to prioritize safety of flight when conflicts arose. The DAA information for all ownship aircraft should be available to the operator at all times, though, as pilots found the ever-present DAA guidance on the baseball cards to be very helpful for deciding where and how to avoid conflicts against unfocused aircraft. This DAA HMI consideration is especially important when the traffic display is limited to focusing on one aircraft at a time during multi-UAS operations. The objective and subjective results infer the Phase 1 MOPS DAA system remains effective at informing timely, appropriate maneuvers for maintaining DWC with multiple assets under control, even without interface solutions known to aid in multi-mission management.

B. Mission Task Efficiency

While DAA task performance did not suffer during nominal situations, there were observed breakdowns in mission task efficiency as the number of controlled UAs increased. Although increased UAs enabled pilots to complete more missions overall, it also increased the amount of time they spent deviated from their flight path after a conflict (Time Off Course) and caused pilots to continue loitering their UAs over AOIs for much longer than required (extra Time on Task). Pilots reported an increase in workload as a function of the number of UAs under their control, with the 5 UAS configuration consistently cited as workload-intensive. Much like the non-significant RT differences, the reduction in mission task efficiency was associated with having to toggle between multiple assets. However, unlike with measured response, there was a significant negative impact on Time on Task as their UA load increased from 1 UAS to 3 UAS and from 3 UAS to 5 UAS. It should be noted that pilots were trained to comply with the mission checklists as precisely as possible, including the assigned loiter time. Pilots were moving on to subsequent missions within 16 sec of completion when controlling a single UAS. This is, not coincidentally, the approximate average amount of time it takes pilots to input an edit and coordinate with ATC, suggesting that they were fully aware of the timer in the 1 UA condition. Extra Time on Task increased by nearly a minute when using 3 UAs and by over three minutes when using 5 UAS, both statistically significant increases, indicating that pilots did not have the bandwidth to closely monitor the timer in those conditions.

Additionally, the Multi-UAS configurations resulted in pilots spending significantly more Time Off Course following a DAA maneuver compared to the single UAS control condition. A review of screen recordings revealed that the extra time off course was caused by pilots temporarily switching their focus to other UAs while the initial UA was performing its avoidance maneuver. Eventually, pilots returned focus to that aircraft to send it back to its previously assigned route. Unfortunately, the lack of a DAA "clear of conflict" aural alert meant that pilots had to either remember to return to that UA on their own or had to notice the removal of the DAA information from that UA's baseball card. No such distractions were possible in the 1:1 configuration. Thus, managing multiple UAs significantly delayed inputs that were not cued by alerting.

C. Automation Support

Interviews with pilots following the study indicated a number of areas where automation would have been beneficial during multi-UAS operations. Pilots reported that 3 UAS was about the most they could comfortably manage on their own, which was in line with assumptions from past research [29, 35]. Around 70% of pilots indicated that they'd be comfortable with automated DAA conflict avoidance for threats requiring immediate action, especially during other high-priority events (e.g., ongoing emergency). At a minimum, pilots would have preferred that the traffic display automatically shift focus to the aircraft in conflict at the onset of a DAA alert. Pilots also indicated that an ideal display would pre-load a maneuver recommendation into the steering interface for severe encounters (i.e., management-by-consent), which has been shown to improve response times [30]. While pilots appear to maintain DWC with multiple UAS at an acceptable rate under manual control, findings imply that an automatic return-to-course function may significantly improve mission task efficiency under multi-UAS conditions. However, the use of automation to offload the tasks of human operators is not straightforward. There are obstacles to implementing this feature, such as logic for determining the appropriate conflict-free 'return' path and allowing proper ATC coordination, but it has the potential to reduce the Time Off Course associated with managing additional UAs.

Pilots also desired automation for mission management, as they wanted to be able to set up all of their mission routes with the desired loiter times in advance. In this study, pilots had to be in the loop for all navigation tasks, which included: setting the target AOI, establishing the appropriate loiter specifications, initiating the 'loiter timer' and setting a new target once the assigned loiter time was achieved. Automating this control loop would have saved the extra Time on Task observed in the multi-UAS configurations, and optimized the use of their controlled assets. These desires are in line with previous research [19, 25, 31], which suggested that human operators can best manage multiple vehicles when they are primarily supervising payload/mission management while automation handles routine navigational control tasks. Interface solutions for multiple vehicle control have been proposed to aid a human operator in schedule management and decision execution [32] and have shown support for management-by-consent compared to management-by-exception [22]. Performance limitations could also be mitigated by a crew configuration (multiple operators for multiple vehicles, referred to as 'M:N') that enables control handoffs between multiple operators during off-nominal events. Past M:N research has supported the usage of plays—i.e., dynamic, human-automation collaboration that considers plans, goals, and resources available—for improving operator awareness during task switching, though this is highly dependent on the operational environment [31]. Adaptive automation would allow for dynamic function allocation, which would help maintain efficiency during various contingencies. Regardless of implementation, the delegation of tasks between humans and automation should complement one another [33], as tunneling effects can arise when shared tasks overlap [34]. The exact number of UAs that can be supported is largely a function of the level of automation support and task load present in a given system. Therefore, the implications of multi-UAS operations are context-dependent, and require further examination in a representative environment.

VII. Conclusion

The Phase 1 DAA system conformed remarkably well to the multi UAS environment, as pilots were able to remain DWC at rates comparable to 1:1 performance. The full progression of visual/aural DAA alerting and guidance appear to get pilots in the loop quickly enough to mitigate drawbacks associated with one operator shifting focus between multiple vehicles, such as delayed response time and reduced mission efficiency. Human-autonomy teaming display solutions may relieve cognitive load during critical situations, and further research is necessary to explore the necessary HMI requirements for automating DAA and/or mission tasks within 1:N and M:N control configurations for increased scalability of UAS-NAS operations.

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