Impact of UAS with Low Size, Weight, and Power Sensors on Air Traffic Controllers' Performance and Acceptability Ratings

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A human-in-the-loop simulation was conducted to evaluate the impact of Unmanned Aircraft Systems (UAS) with low size, weight, and power (SWaP) sensors operating in a busy, low-altitude sector. Use of low SWaP sensors allow for UAS to perform detect-and-avoid (DAA) maneuvers against non-transponding traffic in the sector. Depending upon the detection range of the low SWaP sensor, the UAS pilot may or may not have time to coordinate with air traffic controllers (ATCos) prior to performing the DAA maneuver. ATCo's sector performance and subjective ratings of acceptability were obtained in four conditions that varied in UAS-ATCo coordination (all or none) prior to the DAA maneuver and workload (higher or lower). For performance, ATCos committed more losses of separation in high than low workload conditions. They also had to make more flight plan changes to manage the UAS when the UAS pilot did not coordinate DAA maneuvers compared to when they did coordinate the maneuvers prior to execution. Although the ATCos found the DAA procedures used by the UAS in the study to be acceptable, most preferred the UAS pilot to coordinate their DAA maneuvers with ATCos prior to executing them.

INTRODUCTION

The integration of Unmanned Aircraft Systems (UAS) into the National Airspace System requires UAS to have detect-and-avoid (DAA) capabilities to assist the ground pilot to remain well clear of other traffic. RTCA (2017) developed the Minimum Operational Performance Standards (MOPS) for UAS DAA en route operations that included well clear thresholds of 4,000-ft horizontal miss distance, 450-ft vertical miss distance, and a modified tau of 35 s (Phase 1). En route operations were defined as operations conducted higher than 400 ft above ground level (AGL; i.e., outside of Part 107 airspace) with the UAS transitioning to/from Class A or special-use airspace though Class D, E, and G airspace. RTCA has begun work on Phase 2 of the MOPS that will include, among other additions, terminal area operations and mid-sized UAS that may be equipped with low size, weight and power (SWaP) sensors (see e.g., Fern, Rorie, Roberts, & Monk, 2018).

The limitations associated with low SWaP sensors result in a significantly reduced detection range than had been established in Phase 1 of the MOPS (which assumed a non-cooperative detection range of 6.7 nm). Consequently, the DAA alerting requirements may need to be revised so that there will be adequate time for pilots to respond and/or coordinate with air traffic controllers (ATCos) to accommodate expected low SWaP sensor detection ranges. An initial fast-time simulation was conducted to test four potential DAA well clear definitions for low SWaP-equipped UAS that were smaller than the definition utilized in Phase 1. The proposed Phase 2 definitions reduced the horizontal miss distance and/or the modified Tau component but retained the 450 ft vertical miss distance. The proposed definitions were: Definition 1: 2,000 ft and 15 s; Definition 2: 2,200 ft and 0 s; Definition 3: 1,500 ft and 15 s; and Definition 4: 2,500 ft and 25 s (Chen et al. 2019). The results of these simulations indicated that Definition 2 would preserve the most alerting time under reduced radar surveillance ranges associated with Low SWaP sensors.

Monk, Rorie, Keeler, and Sadler (2020) reported the results of a human-in-the-loop simulation that modeled a UAS with a low SWaP radar (detection range = 3.5 nm) in order to compare DAA well clear Definitions 1 and 2 from Chen et al.'s (2019) study on pilot and DAA system performance. Twelve active-duty UAS pilots flew simulated UAS that were either slow (60 kts) or fast (100 kts) in speed. Ownship encountered non-transponding intruders that were either slow (100 kts) or fast (170 kts) in speed at different geometries. The results showed that at the tested speeds and geometries, both Definition 1 and Definition 2 had reduced DAA alert durations compared to Phase 1. However, Definition 2 was found to mitigate the effect of the smaller detection range by extending the average alert duration by 10 seconds relative to Definition 1. This additional alerting time facilitated slightly higher rates of ATCo coordination in the trials that used Definition 2.

A follow-on fast-time simulation investigated a variety of detection ranges using DAA well clear Definition 2 to determine the effect of range on alerting (Wu, Cone, & Lee, 2019). Wu et al. found that a 2-nm detection range was the "breaking point," below which the DAA alerting time becomes unacceptably short for pilots to respond to the alerts and/or coordinate with ATCos. The present study continues to use DAA well clear Definition 2 (2,200 ft horizontal miss distance, 450 ft vertical miss distance and a 0 s modified tau) to evaluate the impact of low SWaP detection range on ATCo performance and acceptability of UAS DAA maneuvers. The conditions selected presently were not explicit detection ranges but were approximations intended to highlight whether or not the detection range was large enough to facilitate ATCo coordination. The first approximated a lower-end detection range (on the order of 2 nm), which would never provide the pilot time for ATCo coordination prior to an avoidance maneuver. The second approximated a slightly higher detection range (on the order of 3 nm), which, while still limited, would always provide time for ATCo coordination. The primary research question was as follows: *What effect does pilot-ATCo* *coordination have on ATCo performance and acceptability during low SWaP UAS operations?*

For the present study, the following assumptions were made to simplify the problem space. First, we assumed that ATCo communications were exchanged directly with the UAS pilot with no communication delays. Second, only the ATCo aspect of the system was simulated; no UAS systems or displays were used. Instead, all pilots (both manned and unmanned) were confederates following established procedures for scripted encounters. Procedurally, UAS pilot confederates varied whether or not they coordinated with ATCo prior to executing a DAA maneuver. In the “All Coordination” condition, UAS confederates always coordinated their maneuvers with ATCo before maneuvering. They were trained to contact the ATCo with their requested maneuver once the intruder came within ~3 nm of ownship. In the “No Coordination” condition, UAS confederates immediately executed an avoidance maneuver once an intruder was ~2 nm from ownship, only informing the ATCo *after* they had initiated the maneuver. Third, in addition to mode C transponding aircraft [under both instrument (IFR) and visual (VFR) flight rules], a number of non-mode C transponding aircraft were operating in the sector as part of a military mission that allowed for aircraft to turn off their mode C transponder when close to the airports (i.e., within the mode C veil).

Because this is an acceptability study, we used high traffic loads (~1.5 current day traffic) and varied the complexity of the traffic to induce higher or lower workload on ATCo participants (which was determined a priori by subject matter experts). It was hypothesized that the “No Coordination” condition would lead to lower levels of safety and efficiency and higher levels of workload, compared to the “All Coordination” condition. ATCos were also hypothesized to find the “All Coordination” condition to be more acceptable. In addition, it was hypothesized that the negative effects of “No Coordination” will be larger in the high than low workload conditions.

METHOD

Participants

Eight retired ATCos (all male; M = 58 years of age) were recruited through Flight Research Associates, a private company. All participants had experience at Oakland Center (M = 26.38 years), which was the center simulated in this study. Two participants had additional experience with other centers, and two participants had experience with other TRACON facilities. Four participants had experience using Traffic Flow Management software. Three participants had experience with military air traffic control, and three had pilot certificates (M = 2950 flight hours). Each participant was compensated by Flight Research Associates for their full-day participation in the study.

Experimental Design

This study employed a 2 (Workload: Low Workload vs. High Workload) x 2 (ATCo Coordination: No Coordination vs. All Coordination) within-subjects design. Workload was varied by traffic complexity within the sector. The High workload scenarios had more complex traffic situations (e.g., more arrivals on conflicting paths, which required more attention and traffic sequencing procedures from the ATCo participants) compared to the Low workload scenarios.

The dependent measures included air traffic control sector performance metrics: Loss of Separation (LOS = <5nm horizontal and 1,000 ft vertical separation); Average time aircraft travelled through sector; Hand-off accept times, and number of flight plan changes the ATCo made to manage the UAS. In addition, ATCo acceptability ratings on a 5-point Likert-like scale (rating of 3.5 or higher = acceptable) were obtained. The 2 x 2 design resulted in 4 scenarios, each ran once, with the order counterbalanced between participants.

Scenario Design

The scenarios were based on Oakland Center (ZOA) Sector 40/41. This en route/arrival sector has three arrival streams of traffic entering the sector from the north at or below FL240. The arrivals were required to meet crossing restrictions based on their flight plan (3 Standard Terminal Arrival Routes – STARs, see *Figure 1*). Because of the military aircraft in the sector operating below 10,000 ft and two UAS operating in their sector at a blocked altitude of 8,000-10,000 ft, the ATCos were instructed to have the arrival aircraft at or below 7,000 ft (instead of the standard 11,000 ft), and at a speed of 250 kts by the time the aircraft reached the LOZIT, RAIDR, and BOYYS waypoints of the specific STARs.

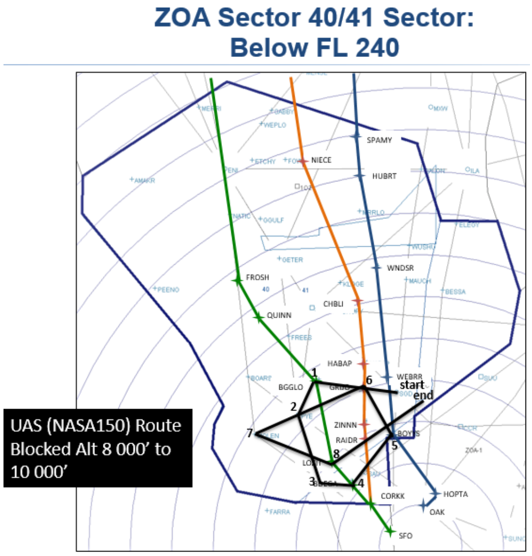

Figure 1. Sector ZOA 40/41 with the three arrival paths into SFO, OAK, and SJC airports. One of the two UAS flight plans is illustrated (numbered in black). The second UAS flew an independent route.

The UAS pairs were conducting air-sampling missions around the airport and crossed all 3 arrival streams. The UAS were cleared for a block altitude of 8,000-10,000 ft Mean Sea Level (MSL). The UAS had simulated Predator “B” characteristics and traveled at a maximum speed of 100 kts. There was no convective weather present.

Post-Scenario Questionnaires

In addition to the performance metrics captured during the scenarios described earlier, we administered questionnaires to measure the controller's subjective assessment of their situation awareness (using the Situation Awareness Rating Technique, SART) and workload (using the NASA-Task Load Index, NASA-TLX) at the end of each scenario. In addition, custom questionnaires were used to obtain ATCo's acceptability ratings regarding the scenarios tested using 5-point Likert-like scales.

Procedure

The simulation was run in the Center for Human Factors in Advanced Aeronautics Technologies at California State University Long Beach. The participants first filled out a consent form and demographics survey, and then were provided a briefing about the simulation, including the general purpose, assumptions, and ATCo's tasks, roles, and responsibilities. Participants then ran in training scenarios for familiarization and practice. During the first five minutes of the familiarization run, confederates were instructed to not call in any aircraft to provide the participants with practice on the features and controls of the interface. The familiarization run included IFR overflights, IFR arrivals, and transponding VFR overflights. Confederates began calling in aircraft for the last 15 minutes of the familiarization run. Participants were then asked if they were comfortable to move on to the next two 30-minute training runs; if not, they would repeat another 20-minute familiarization run.

The first training run added two UAS to the airspace, which followed the same flight plan as in the experimental runs. The second training run added non-transponding VFR aircraft (i.e., their data blocks did not display altitude, speed, etc.) to the airspace as primary targets. At times, non-transponding VFR aircraft conflicted with the UAS, therefore the UAS pilot needed to coordinate DAA maneuvers with the participant ATCos before or after performing them. After completing the second training run, participants filled out the SART, NASA TLX, and post-trial questionnaire and were asked if any further clarification was needed for the questionnaires.

After training, participants began the experimental trials. Each of the four experimental scenarios was 40 minutes long, and following each scenario, participants filled out the SART, NASA TLX, and post-trial questionnaire. Participants were given breaks and a 45-minute lunch. When all trials were completed, participants filled out the post-simulation questionnaire and participated in a debriefing session.

RESULTS

ATC Performance

A series of 2 (ATCo Coordination: All Coordination or No Coordination) x 2 (Workload: Low or High) repeated measures ANOVAs were run on the metrics of ATCo performance: loss of separation (LOS) for a measure of safety; aircraft time through sector for efficiency, and hand-off accept time for workload. For all analyses, we used an alpha level of .05.

Loss of Separation (LOS). A main effect of workload was found for the total number of LOS with IFR aircraft (including the UAS), $F(1,7) = 7.99$, $p = .026$, with more LOS occurring in the scenarios with the high ($M = 4.31$) than low ($M = 3.19$) workload condition, see *Figure 2.*

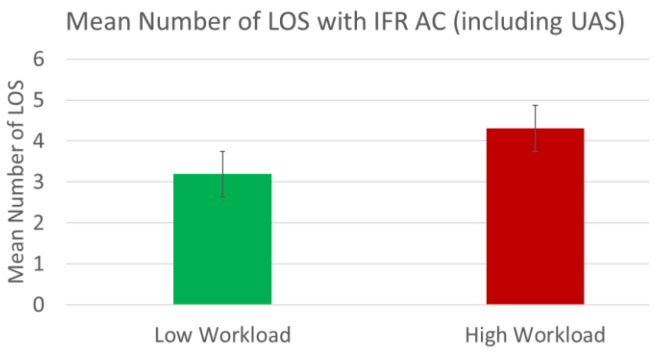

Figure 2. Mean Number of Losses of Separation with IFR Aircraft by Workload Condition.

Time of Aircraft in Sector. Separate analyses were run for the amount of time overflight and arrival aircraft traveled through the ATCo's sector. For overflights, there was an interaction of coordination by workload, $F(1,7) = 26.69$, $p < .001$. There was no difference in time in sector for the high workload condition, but for the low workload condition, ATCos were more efficient in the All Coordination ($M = 937$ s) than No Coordination ($M = 1004$ s) conditions, see *Figure 3.* No other effects were significant.

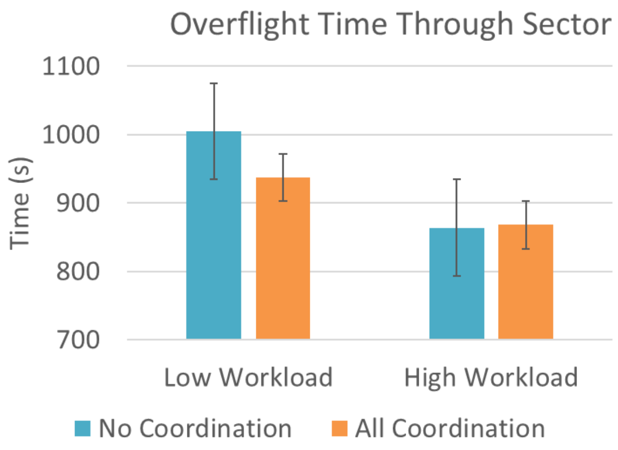

Figure 3. Time of overflights traveled through sector by workload condition and by coordination.

Handoff Accept Time. There were no significant effects or interactions.

Strategies. The number of flight plan changes made to the IFR aircraft to avoid conflict with the UAS was examined. Only the main effect of coordination was significant, $F(1,7) = 5.83$, $p = .046$, see *Figure 4*. More flight plan changes were made, on average, in the No Coordination ($M = 1.94$ changes) than All Coordination ($M = 0.69$ changes) condition.

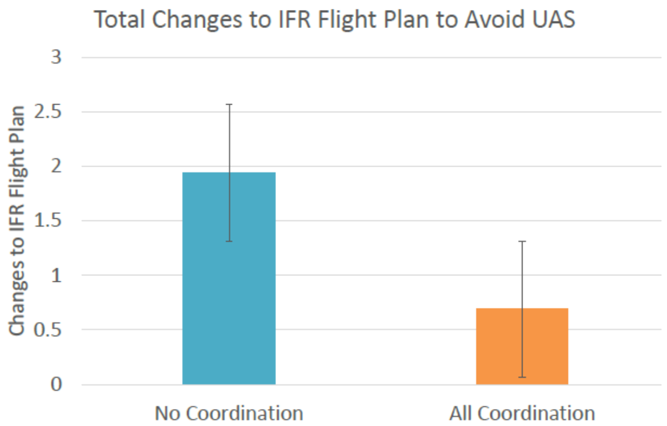

Figure 4. Main effect of coordination for total changes made to IFR aircraft to avoid UAS.

NASA TLX (Subjective Workload) and Situation Awareness Rating Technique (SART)

Composite NASA TLX and SART scores were submitted to a 2 (Coordination: No Coordination or All Coordination) x 2 (Workload: Low or High) ANOVA. For the TLX, only the main effect of workload condition was significant, $F(1,7) = 14.53$, $p = .007$, where the workload rating was higher in the high ($M = 59.6$) than low ($M = 51.2$) workload scenarios, see *Figure 5*. There were no significant effects for the SART.

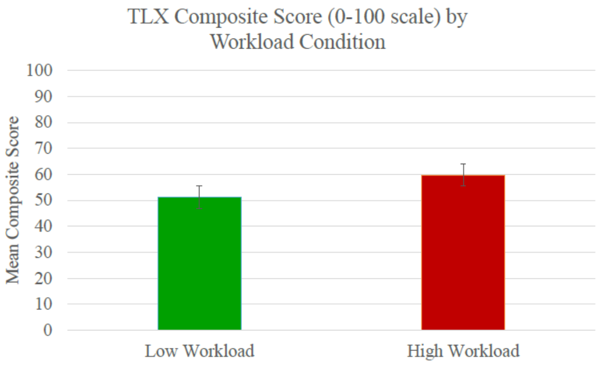

Figure 5. NASA TLX workload ratings for the low and high workload conditions.

Acceptability Ratings

Post Scenario Questionnaire. A series of 2 (Coordination: No Coordination or All Coordination) x 2 (Workload: Low or High) ANOVAs were performed on the ATCos' ratings of acceptability to questions on the post scenario and post simulation questionnaires. Significant effects are summarized in Table 1.

An average acceptability rating of 3.5 or higher (out of 5) on the Likert scale were considered to be indicative of the ATCos' agreement with a given statement. As a result, one-sample t-tests with the test value of 3.5 were performed. Significant effects are summarized in Table 2.

Post Simulation Questionnaire. In addition to the acceptability ratings of the overall operations and procedures, the ATCos were asked to rate specific components of the simulation. Two questions yielded mean ratings above the 3.5 test value. For the statement, *Having the two UAS operating in my sector made my workload ___ compared to standard operations*, the ATCos indicated that the workload was somewhat higher ($M = 4.0$, $p = .03$). For the statement, *ATC should always be notified when the UAS is in conflict with non-cooperative traffic*, ATCos significantly agreed with it ($M = 4.38$, $p < .001$).

Question	Main Effect	Means
The location of VFR non-mode "C" aircraft (i.e., primary targets) affected my ability to manage my airspace efficiently.	Effect of Workload, $p = .03$	Low= 2.38 High= 2.62
The location of VFR non-mode "C" aircraft (i.e., primary targets) affected my ability to manage my airspace efficiently.	Effect of Coordination, $p = .02$	No = 2.69 All = 2.31
The location of VFR non-mode "C" aircraft (i.e., primary targets) affected my airspace's traffic flow.	Effect of Coordination, $p = .03$	No = 2.69 All = 2.44
The UAS traffic operating in my airspace affected my airspace's traffic flow.	Effect of Coordination, $p = .02$	No = 3.56 All = 2.75
The UAS traffic operating in my airspace affected my airspace's traffic flow.	Workload x Coordination, $p = .01$	Low/No = 3.63 Low/All = 2.25 High/No = 3.50 High/All = 3.25
The number of VFR aircraft (i.e., cooperative, Mode "C" transponder AC) affected my airspace's traffic flow.	Workload x Coordination, $p = .04$	Low/No = 2.50 Low/All = 2.75 High/No = 3.50 High/All = 2.63
The location of VFR aircraft (i.e., cooperative, Mode "C" transponder AC) affected my strategies for separating IFR traffic.	Effect of Coordination, $p = .049$	No = 2.75 All = 2.44
The location of VFR non-mode "C" aircraft (i.e., primary targets) affected my strategies for separating IFR traffic.	Effect of Coordination, $p = .03$	No = 2.69 All = 2.44

Table 1. Mean ratings for post-scenario questions. Scale 1 (disagree) to 5 (agree).

Question	**The DAA procedures employed by the UAS pilots in the scenario were acceptable.**			
Condition	Low/No	Low/All	High/No	High/All
	M = 4.0	*M* = 4.0	*M* = 3.88	*M* = 4.13
Question	**Overall, UAS operations used in the scenario were acceptable for my sector.**			
Condition	Low/No	Low/All	High/No	High/All
	M = 4.0	*M* = 4.13	*M* = 4.0	*M* = 4.13
Question	**Overall, UAS traffic avoidance maneuvers in my sector were safe.**			
Condition	Low/No	Low/All	High/No	High/All
	not sig	*M* = 4.38	*M* = 4.0	*M* = 4.13

Table 2. Mean ratings for post-scenario questions. Scale: 1 (disagree) to 5 (agree).

Debriefing Interviews

After completing all scenarios and the post-simulation questionnaire, participants engaged in a debriefing session where they were briefed on the goals of the simulation and asked open-ended questions. Participants' responses were transcribed and coded into categories of similar responses. Below, we provide a summary of their responses to three of the debriefing questions.

What are your general thoughts about the UAS pilot coordination with ATC for these DAA maneuvers?

Four of the eight participants indicated that they did not have an issue with the coordination procedures used in the present study (i.e., coordinate if time permits; otherwise perform maneuver then inform the ATCo). Three of the participants indicated that they would prefer that the UAS pilots always contact them before initiating the maneuver. Only one participant would prefer that they always be notified after the maneuver.

Were the DAA coordination procedures/maneuvers used in the present simulation acceptable to you? If not, when were they not acceptable?

Seven of the eight participants indicated that the coordination procedures used in the present study were acceptable. One participant believed that he could provide better conflict resolutions for the encounters than what the UAS pilot performed.

In terms of distance and time, how far in advance would coordinating before maneuvering be useful?

Four of the eight participants indicated that they needed at least 3 nm of separation before maneuver coordination can be useful. Three indicated that at least 5 nm is needed before maneuver coordination can be useful. Only one participant indicated that a 2 nm range would be useful.

SUMMARY AND CONCLUSION

Overall, ATCos in this simulation showed a preference for UAS pilots to coordinate with air traffic control prior to making maneuvers, even in response to DAA alerts. However, all ATCos understood that when necessary, the UAS will move to avoid a collision prior to coordination. The ATCos in this study made more traffic calls to UAS and VFR aircraft in the No Coordination conditions compared to the All Coordination conditions, which could lead to increased workload for ATCos. Although most ratings on the impact of UAS, IFR, and VFR (both transponding and non-transponding) were around the mid-point of neutral, the ATCos showed higher agreement with the statements indicating an impact on the sector's efficiency and ATC strategies in the No Coordination than All Coordination condition. Nonetheless, the ATCos indicated that the DAA procedures employed by the UAS pilots in the simulation were ultimately acceptable. Finally, most ATCos indicated that for coordination to be useful, the UAS and intruder need to be separated by at least 3 nm.

Ultimately, the requirement for low SWaP sensor detection ranges is going to be driven by multiple factors, such as the hardware and software capabilities of these new sensor types. The goal of this current study was to inform the wider UAS community on the tradeoff between smaller and larger detection ranges in terms of pilot ability to coordinate with ATCos. Taken together, the results indicate that the ATCo in this experiment would *prefer* the coordination that a larger detection range enables, but they do not consider it a requirement. When coordination was not possible at the smaller detection ranges associated with low SWaP sensors, ATCo indicated that the priority is for the UAS pilot to maneuver immediately to maintain minimum safe distance between aircraft, followed by ATCo notification, which is consistent with established Collision Avoidance guidelines (e.g., Traffic Alert and Collision Avoidance System, TCAS II). Further research is needed to determine whether such an approach is appropriate from the perspective of UAS pilot acceptability and, more importantly, safety.

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