UAS Integration in the NAS Project
Part Task 6 V&V Simulation
Primary Results

Conrad Rorie: Research Engineer, Human Systems Integration
Lisa Fern: Senior Research Engineer, Human Systems Integration
Jay Shively: Project Engineer, Human Systems Integration
Confesor Santiago: Project Engineer, SSI

RTCA SC-228
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Background

• **Purpose:**
  – Conduct final V&V activity in support of SC-228 DAA HMI requirements for displays, alerting and guidance

• **Goals:**
  – Implement the display, alerting and guidance requirements as close as possible in simulation
    • Less emphasis on independent variables
  – Test in representative simulated flight environment
    • E.g., airspace w/ ATC in-the-loop, multiple UAS missions, high-fidelity surveillance models
  – Expected outcome/product(s): pilot performance data to validate final DAA MOPS
    • Losses of Well Clear
    • Pilot response times
    • Additional pilot behavior: TCAS compliance, type/size of maneuvers, ATC coordination

• **Overall Research Question:**
  – Do we see comparable pilot performance using the minimum display requirements (as currently defined in the draft MOPS) to previous simulations
Background

• Changes to expected test set up
  – Planned to run with high fidelity surveillance model for duration of experiment
    • Unable to integrate the model & tune DAA system in time
  – Planned to run with TCAS II for duration of experiment
    • Following first half of data collection, subjective feedback from pilots indicated that they were losing trust in DAA system with repeated TCAS RAs in absence of prior DAA alerting
      – Concerned it impacted how pilots responded to scripted encounters
    • Removed TCAS II from simulation environment for second half of data collection
      – Allowed experimental design to remain balanced
Method: Experimental Design

- **Experimental Design**
  1. **Display Configuration (within-subjects)**
     1. Standalone DAA display (decoupled from moving map/TSD)
     2. Integrated DAA display (collocated with moving map)
  2. **Ownship Equipage (between-subjects)**
     1. TCAS II-equipped
     2. No TCAS II

- **Participants:**
  - 16 active duty UAS pilots
    - Average Age: 49
    - Manned Flying Experience Total Hours: 5000
    - Unmanned Flying Experience Total Hours: 2100
Method: Experimental Design

Standalone Configuration

Notes:
• Pilot could **only make uploads via TSD**; DAA Display only served as a traffic reference
• Pilots trained on how to adjust orientation on both DAA & TSD displays
  • North Up vs. Track Up, and whether orientations matched, was up to pilot discretion
Method: Experimental Design

Integrated Configuration

TSD w/ DAA Display

Side Panel
## Method: Experimental Design

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Pilot Action</th>
<th>Buffered Well Clear Criteria</th>
<th>Time to Loss of Well Clear</th>
<th>Aural Alert Verbiage</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="TCAS RA" /></td>
<td>TCAS RA</td>
<td>- <strong>Immediate action required</strong>&lt;br&gt;- Comply with RA sense and vertical rate&lt;br&gt;- Notify ATC as soon as practicable after taking action</td>
<td>*DMOD = 0.55 nmi&lt;br&gt;*ZTHR = 600 ft&lt;br&gt;*modTau = 25 sec</td>
<td>0 sec (+/- 5 sec) (TCPA approximate: 25 sec)</td>
<td>“Climb/Descend”</td>
</tr>
<tr>
<td><img src="image" alt="DAA Warning Alert" /></td>
<td>DAA Warning Alert</td>
<td>- <strong>Immediate action required</strong>&lt;br&gt;- Notify ATC as soon as practicable after taking action</td>
<td>DMOD = 0.75 nmi&lt;br&gt;HMD = 0.75 nmi&lt;br&gt;ZTHR = 450 ft&lt;br&gt;modTau = 35 sec</td>
<td>25 sec (TCPA approximate: 60 sec)</td>
<td>“Traffic, Maneuver Now” x2</td>
</tr>
<tr>
<td><img src="image" alt="Corrective DAA Alert" /></td>
<td>Corrective DAA Alert</td>
<td>- On current course, <strong>corrective action required</strong>&lt;br&gt;- Coordinate with ATC to determine an appropriate maneuver</td>
<td>DMOD = 0.75 nmi&lt;br&gt;HMD = 0.75 nmi&lt;br&gt;ZTHR = 450 ft&lt;br&gt;modTau = 35 sec</td>
<td>55 sec (TCPA approximate: 90 sec)</td>
<td>“Traffic, Avoid”</td>
</tr>
<tr>
<td><img src="image" alt="Preventive DAA Alert" /></td>
<td>Preventive DAA Alert</td>
<td>- On current course, corrective action <strong>should not be required</strong>&lt;br&gt;- Monitor for intruder course changes&lt;br&gt;- Talk with ATC if desired</td>
<td>DMOD = 0.75 nmi&lt;br&gt;HMD = 1.0 nmi&lt;br&gt;ZTHR = 700 ft&lt;br&gt;modTau = 35 sec</td>
<td>55 sec (TCPA approximate: 90 sec)</td>
<td>“Traffic, Monitor”</td>
</tr>
<tr>
<td><img src="image" alt="Guidance Traffic" /></td>
<td>Guidance Traffic</td>
<td>- <strong>No action required</strong>&lt;br&gt;- Traffic generating guidance bands outside of current course</td>
<td>Associated w/ bands outside current course</td>
<td>x</td>
<td>N/A</td>
</tr>
<tr>
<td><img src="image" alt="None (Target)" /></td>
<td>None (Target)</td>
<td>- <strong>No action required</strong>&lt;br&gt;- No coordination required</td>
<td>Within surveillance field of regard</td>
<td>x</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* These values show the Protection Volume (**not well clear volume**) at MSL 5000-10000ft (TCAS Sensitivity Level 5)
### Method: Experimental Design

**Week 1 – Ownship Equipped with TCAS II**

<table>
<thead>
<tr>
<th>Cooperative Aircraft</th>
<th>Name</th>
<th>Aural Alert Verbiage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>TCAS RA</td>
<td>“Climb/Descend”</td>
</tr>
<tr>
<td>DAA Warning Alert</td>
<td>“Traffic, Maneuver Now” x2</td>
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<td>Preventive DAA Alert</td>
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</tr>
<tr>
<td>Guidance Traffic</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>None (Target)</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-Cooperative Aircraft</th>
<th>Name</th>
<th>Aural Alert Verbiage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>DAA Warning Alert</td>
<td>“Traffic, Maneuver Now, Traffic” x2</td>
</tr>
<tr>
<td>Corrective DAA Alert</td>
<td>“Traffic, Avoid”</td>
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<td>Guidance Traffic</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>None (Target)</td>
<td>N/A</td>
<td></td>
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</tbody>
</table>
### Method: Experimental Design

**Week 2 – Ownship Not Equipped with TCAS II**

<table>
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<tr>
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</tr>
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<tr>
<td>![Symbol]</td>
<td>DAA Warning Alert</td>
<td>“Traffic, Maneuver Now, Traffic” x2</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>Corrective DAA Alert</td>
<td>“Traffic, Avoid”</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>Preventive DAA Alert</td>
<td>“Traffic, Monitor”</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>Guidance Traffic</td>
<td>N/A</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>None (Target)</td>
<td>N/A</td>
</tr>
</tbody>
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<td>![Symbol]</td>
<td>DAA Warning Alert</td>
<td>“Traffic, Maneuver Now, Traffic” x2</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>Corrective DAA Alert</td>
<td>“Traffic, Avoid”</td>
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<td>“Traffic, Monitor”</td>
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<tr>
<td>![Symbol]</td>
<td>Guidance Traffic</td>
<td>N/A</td>
</tr>
<tr>
<td>![Symbol]</td>
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Method: DAA Guidance Bands

- The JADEM Omni Bands are a form of suggestive maneuver guidance that display relative threat level of various heading and altitude options
  - Headings ‘bands’ appear on the inner range ring
  - Altitude ‘bands’ appear to the far left of the TSD
- Both bands are updated constantly to reflect the most up-to-date information
Method: Example DAA Encounter
Method: Well Clear Recovery

- If algorithm determines *horizontal* maneuver will lead to greatest separation:
  - Shown optimal heading region ("wedge") to fly next to ownship

- If algorithm determines *vertical* maneuver will lead to greatest separation:
  - Green altitude block ("wedge") within altitude tape shows optimal altitude range

**NOTE:** No aural alert at this stage
Method: Example WCR Encounter
Method: TCAS II Display

- If TCAS RA is generated:
  - Green band in vertical velocity indicator shows direction and rate of climb to be achieved
- Aural alert generated
  - E.g. “Climb, Climb”
Method: Example TCAS Encounter
Method: Simulation Environment

• Task:
  – Fly simulated MQ-9 through Class E airspace (Oakland Center – ZOA 40/41)
    • Navigate along pre-filed routes (used AFRL’s Vigilant Spirit Control Station)
      – 2 different routes flown
    • Maintain well clear
    • Coordinate with ATC (time permitting)
    • Attend to secondary tasks (e.g., chat messages, system alerts)

• Pre-planned conflicts with ownship
  – 6 scripted encounters predicted to lose well clear
    • 1/2 with cooperative traffic
    • 1/2 with non-cooperative traffic
  – 2 scripted encounters predicted to become preventive self separation alerts
Method: Simulation Environment

• Simulation Hardware/Software:
  – Vigilant Spirit Control Station (VSCS) from AFRL
    • Standalone & integrated DAA configurations
    • Integrated TCAS II RA alerts and guidance
    • Internal traffic generation tool used for approx. 70% of encounters
  – TCAS II v 7.0 logic (with 7.1 aural alerts) [when enabled]
  – JADEM v5.6.7.1 DAA System
    • DAA alerting
    • DAA guidance (Omni Bands)
    • Well Clear Recovery guidance
    • Perfect surveillance data (no uncertainty models applied)
Method: Simulation Environment

- Mission routes located within Oakland Center (ZOA40/41)
  - Both mission routes flown simultaneously
    - 2 UAS being flown from separate GCS
  - Includes a variety of classes of airspace
    - IFR traffic into and out of SFO and OAK
    - VFR traffic from smaller airports (e.g., STS and APC)
Method: Simulation Environment

- **Fire Line Track (HAWK21)**
  - Level at 9000’
  - Serving as air asset for California Department of Forestry for fire burning north of Clear Lake
Method: Simulation Environment

- **Air Sampling Track (SAMP61)**
  - Starts at 10000’, contains climb & descent
  - Serving as air asset for California Air Resources Board to measure quality of air east of Santa Rosa
Method: Simulation Environment

- Simulation confederates
  - NATCA controller managed UAS and manned traffic within ZOA 40/41
    - Simulated manned traffic based on actual sector activity
  - Pseudo-pilots managed all manned traffic to provide dynamic sector activity
  - ATC SME operated as ‘ghost’ controller to ensure conflicts were generated
  - HSI researcher operated VSCS internal conflict generator
Key Research Questions

• Loss of Well Clear
  – Did display configuration impact rate or severity of LoWC?
  – Any other observable factors for instances of LoWC?

• Response Time
  – Did display configuration impact how quickly pilots were able to perform the DAA task?
    • If so, which component of the DAA task did display configuration have an effect on?
  – Did any other factors impact pilot response time (e.g., trial, mission type, ownership equipage, intruder equipage)?
Key Research Questions

- **TCAS II RA Metrics**
  - Number of RAs issued
  - Pilot response time to RAs and rate of compliance
  - How often were pilots ‘well clear’ when an RA was issued?
    - Did presence of TCAS II degrade pilot performance or understanding of the DAA system?

- **Additional Pilot Metrics**
  - ATC coordination
    - How often did pilots gain approval prior to maneuvering away from, or back to, their mission route?
  - Maneuver Statistics
    - Did pilots overwhelmingly prefer certain types of maneuvers?
      - Did any variable (e.g., display configuration) impact how they maneuvered?
    - Did size of maneuvers vary between conditions?
LOSS OF WELL CLEAR
Loss of Well Clear Proportions

- 16 total LoWC (out of 466 encounters) with encounters that appeared as a Corrective or Warning at First Alert
  - Standalone = 9 total LoWC; Integrated = 7 total LoWC
• 5 LoWC (out of 436 encounters) with encounters that appeared as a Corrective at First Alert (dropping those that started as Warning)
  – Standalone = 4 LoWC; Integrated = 1 LoWC
Loss of Well Clear Proportions

- 11 LoWC (out of 30 encounters) with encounters that appeared as a Warning at First Alert (dropping those that started as Corrective)
  - 29 of these were from single encounter, which was scripted to make 90deg blunder into ownship to cause immediate DAA Warning
  - Standalone = 5 LoWC; Integrated = 6 LoWC

Proportion of WARN that Proceeded to LoWC

<table>
<thead>
<tr>
<th>Display Configuration</th>
<th>Proportion of LoWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standalone</td>
<td>0.3571</td>
</tr>
<tr>
<td>Integrated</td>
<td>0.4000</td>
</tr>
</tbody>
</table>
Diagnosing LoWC

- 11 LoWC when intruder was Warning at First Alert
  - *Insufficient time to respond*
    - 8 LoWC occurred when pilots had less than 15sec to LoWC
  - *Insufficient upload*
    - 2 LoWC where pilot uploaded an altitude despite bands showing all red
    - 1 LoWC where pilot was too slow making upload
Diagnosing LoWC

• 5 LoWC when intruder was Corrective at First Alert
  – Display Configuration
    • Standalone (4 LoWC)
      – 1 pilot made multiple ineffective maneuvers, likely compounded by fact that the DAA display was in different orientation than TSD
      – 2 pilots made ineffective heading changes, likely compounded by the fact that the bands did not coincide with control interfaces
      – 1 pilot failed to notice altitude bands were no longer clear by time upload was made
    • Integrated (1 LoWC)
      – 1 pilot failed to notice altitude bands were no longer clear by time upload was made
  – Trial (4 LoWC)
    • 4 occurred during first trial of the day
LoWC Example

- Case of DAA display & TSD having different orientations
RESPONSE TIME DATA
Metrics

- Primary response time metric is Total Response time
  - Comprised of Initial Response Time, Initial Edit Time and Total Edit Time
Total Response Time

- Pilots sent final upload to their aircraft 2 sec faster (~10%) in Integrated display configuration (not statistically different ($p > .05$))
- More pronounced difference between displays when separated by alert level
  - Pilots sent final upload 5.5 sec faster (~30%) in response to DAA Warning alerts in Integrated display configuration
  - No statistical difference (large variability, a result of small sample size)
Total Response Time

• Compared to Part Task 5, times are generally faster in PT6, with exception of pilot responses to DAA Warnings in the Standalone condition.
Initial Response and Initial Edit (First Upload)

- Bulk of the reduction in total response times for Warning alerts is that pilots initiate their response much earlier
  - To a lesser extent, pilots also spend less time implementing their edits
Subsequent Edits (Additional Uploads)

- Complicating things was the fact that pilots often sent a late upload in response to well clear recovery, leading to larger *total* edit times for Warnings than for Correctives.

![Bar chart showing seconds for CORR and WARN for Standalone and Integrated display configurations.](chart.png)
Aircraft Response Time

- If you only consider first upload, as opposed to final upload as used by total response time, we see response times more in line with expectations
  - Comparison to PT5 is cleaner, although response to Warning in Standalone configuration is still slower in PT6
Key Research Questions

• TCAS II Research Questions:
  – Under nominal conditions, how many encounters progress to a corrective RA?
  – What is the relative average response time for pilots responding to a corrective RA?
    • How does it compare to response times to corrective and warning alerts?
  – What is the compliance rate to corrective RAs?
  – Were there instances of near mid air collisions (NMACs)?
Conclusions

• Saw expected pilot performance with previous simulations using minimum display, alerting & guidance requirements
  – LoWC metrics & pilot response times
• Standalone display resulted in little to no performance differences compared to the Integrated display configuration
  – Slightly longer pilot response times (expected)
  – While Standalone display led to more LoWC against threats that were Corrective at First Alert, this almost always happened in first trial of the day
    • Fact that Integrated configuration only had a single LoWC suggests pilots may need more time or training on Standalone displays than on Integrated
• Additional observations
  – Altitude tape needs to be on right side DAA display (frequently disregarded) and as close to the center of their field of view as possible
    • In both the Standalone and Integrated conditions pilots uploaded a vertical maneuver that was no longer conflict-free according to DAA altitude bands
  – Excessive TCAS RAs while well clear impact pilots’ trust of DAA alert structure
  – Longer run times (1 hr vs. 38 min) saw some fatigue effect
    • Initial response times went up in trial 4 compared to first 3 trials of the day
    • Didn’t seem to impact overall performance