Hazard Perception & Avoidance (HPA)

Assured Vehicle Automation 1 Sim - Results Outbrief

January 24, 2023

HPA Background

- Hazard Perception and Avoidance (HPA) is a technical area under Advanced Air Mobility's (AAM) Automated Flight and Contingency Management (AFCM) sub-project
  - Collecting human-in-the-loop simulation and flight test data to inform standards development for a tactical avoidance system for AAM
  - Building toward UML-4; **assuming an onboard pilot** with increased automation support

- Using the FAA's Airborne Collision Avoidance System for Rotorcraft (ACAS Xr) as our tactical conflict detection and resolution technology

ACAS Xr Background

- ACAS Xr provides Detect and Avoid (DAA) and Collision Avoidance (CA) functionality
  - DAA is caution-level, suggestive, and triggers ~90 seconds from CPA
  - CA is warning-level, directive, and triggers ~30 seconds from CPA

- ACAS Xr issues a variety of Collision Avoidance alerts - i.e., Resolution Advisories (RAs)
  - **Horizontal** RAs command a *target track angle*
  - **Vertical** RAs command a *target vertical speed*
  - **Blended** RAs command a target track & vertical speed *simultaneously*

- ACAS Xr "Modes"
  - TA/RA Mode: similar to TCAS II; Collision Avoidance only
    - Traffic Advisories (TAs) are caution-level and issued prior to Resolution Advisories (RA)
  - DAA Mode: similar to ACAS Xu; DAA + CA
    - DAA alerting and guidance replaces TAs
    - Pilots maneuver at their discretion against DAA alerts

DAA Alert

Blended RA

Study Objectives

- Present Xr in a higher-fidelity environment than previous Part Task study:
  - Full motion simulator
  - Turbulence
  - Out-the-window visual traffic

- Examine pilots' use of ACAS Xr v2 in multiple phases of flight with both Xr Modes
  - Fully leverage Xr v2 features:
    - Use radar altimeter data to inform low altitude RA behavior
    - Utilize ability to designate "terminal-area intruders" in DAA Mode
    - Display airspeed-based DAA guidance
  - Emulate "Traffic Advisories" in TA/RA Mode
    - v2 does not issue TAs, so the Corrective DAA alert was used to approximate it

Experimental Design

- Independent Variables

  - **Phase of Flight** (3 levels; within-subjects)
    - *Cruise* – cruise speed of 110kts, starting altitude 500-1500ft
    - *Hover* – hover speed of 10kts, starting altitude 500-1500ft MSL
    - *Approach* – straight-in approach, speed 70kts, starting altitude 700-1100ft, 6° glide slope

  - **ACAS Xr Mode** (2 levels; within-subjects)
    - *TA/RA Mode*: DAA alerting & guidance is suppressed; RAs issued nominally in Cruise and Hover
      - Traffic Advisory (TA) *replaces* the DAA guidance
      - Terminal area behavior: ACAS switched to "TA-Only" mode at start of encounter, RAs suppressed
      - Low altitude behavior: fixed Descend RA inhibit below 750ft
    - *DAA Mode*: DAA & RA alerting and guidance is issued nominally in Cruise and Hover
      - Terminal area behavior: DAA alerting and horizontal RAs suppressed against terminal area intruders
      - Low altitude behavior: radar altimeter used to inform Ground Point Obstacle Awareness (GPOA) feature

Experimental Design

- Experimental Scenarios
  - Encounters flown as ~5-minute vignettes, all in the SF bay area
    - Scripted conflicts varied by intruder angle, relative altitude, & vertical/horizontal rate
  - Scenarios counterbalanced by the ACAS Xr Mode and Phase of Flight variables
    - Pilots flew with the DAA or TA/RA Mode on Day 1, and experienced the other condition on Day 2
  - Ownship initialized in auto-pilot, but participants had to disengage the auto-pilot and ***manually respond*** to the ACAS Xr alerting & guidance (i.e., no automated RA response)
    - Disengaging auto-pilot only required a stick deflection in the cruise and approach phases
    - Hover scenarios required the pilot to press a button that de-activated the 'hover mode' before exiting the hover
  - No ATC interaction or background traffic was included in *any* of the phases

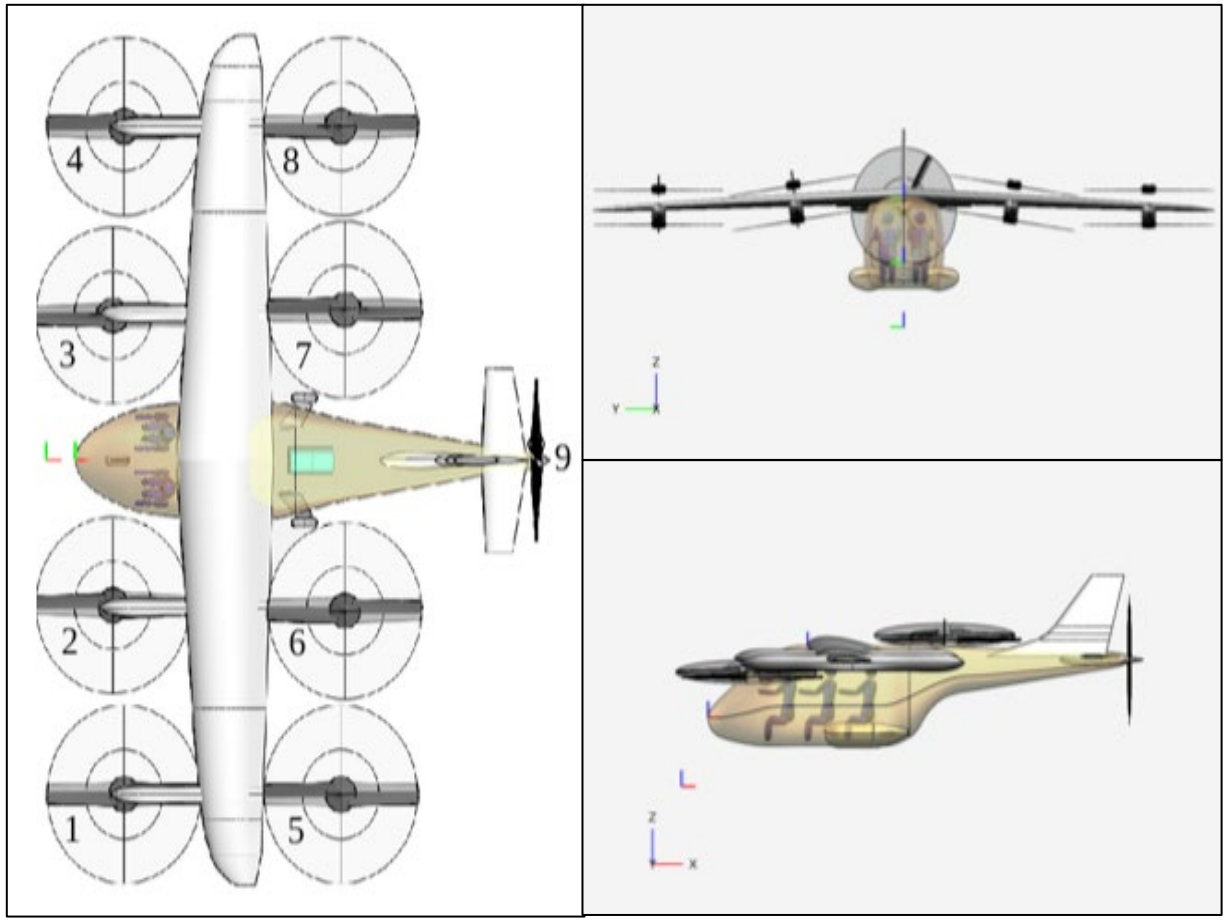
Participants

- 6 participants were recruited
  - All male
  - Avg. age = 51 (SD=9)
  - Each participated for 2 days total, which included ½ day of simulator & ACAS training

- Experience:
  - All had rotorcraft experience
    - Avg. rotorcraft flight hours = 683 (SD=1154)
    - 5/6 also had fixed-wing experience
  - Half had experience with TCAS II
  - 5/6 were IFR rated
  - 5/6 had nap of the earth experience for multiple environments

Aircraft Model

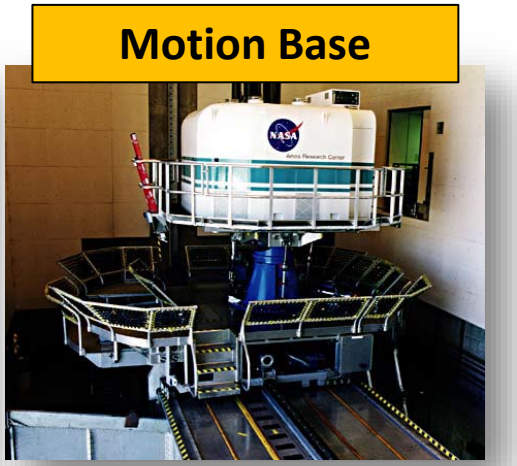
- Vehicle Model
  - NASA's **Lift Plus Cruise** (LPC) hybrid electric Vertical Takeoff and Landing (eVTOL) model
  - Used for ownship and intruder aircraft
- Capable of fully transitioning from thrust-borne flight to wing-borne lift
- Characteristics
  - Cruise speeds: 70-110KTAS
  - Altitude: 500-1500ft MSL
  - Max. bank: 40°
  - Max. climb rate: 1000fpm
- No sensor noise modeled
  - Perfect ownship and intruder data

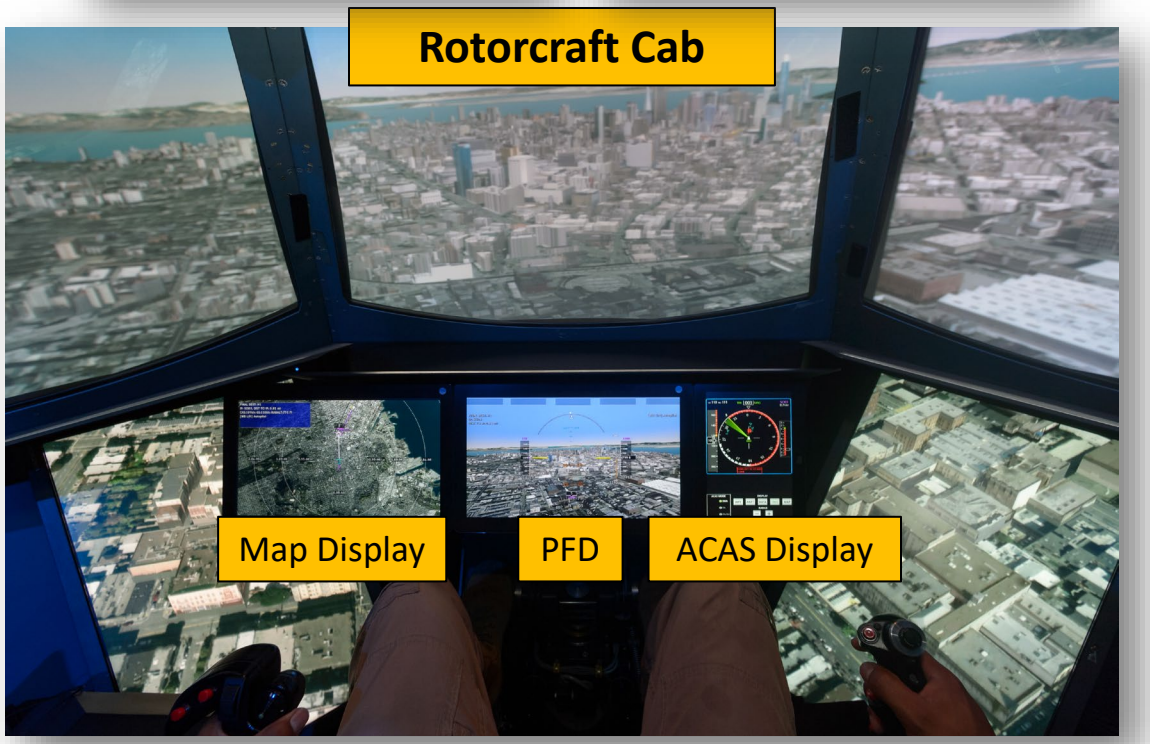


Cab Configuration

- Study utilized NASA Ames' **Vertical Motion Simulator** (VMS) Rotorcraft Cab (R-Cab)
  - 6D motion, turbulence & out the window visual traffic

- Cab controls and displays
  - 2 side-stick controllers & rudders
    - Left = accelerate/decelerate
    - Right = commands vertical rate & bank angle
      - Deflecting right stick disengages autopilot
      - Thumb button toggles on/off hover mode
  - Top-down map display (left)
  - PFD display with camera underlay (center)
  - **ACAS Xr traffic display (right)**





ACAS Xr Display

TA/RA Mode

- *Traffic Advisory* (TA) issued first
  - Visual & aural alert (“Traffic, Traffic”)
  - Not used to maneuver - no maneuver guidance
  - Pilot can try to visually acquire traffic

- *Resolution Advisory* (RA) eventually issued
  - Visual & aural alert (e.g., “Climb, Climb”, “Turn Right, Turn Right”)
  - Vertical and/or horizontal guidance dictates how pilot maneuvers
  - Maneuver expected within 5 seconds

DAA Mode

- *DAA Corrective* alert issued first
  - Visual & aural alert (“Traffic, Avoid”)
  - Guidance “banding” used by pilot to determine if/how to maneuver
  - Airspeed, heading and vertical speed bands

- *Resolution Advisory* (RA) issued if not resolved
  - Presentation same as TA/RA Mode

RESULTS

OBJECTIVE METRICS

by Phase of Flight:

RA & DAA Response Times

Losses of Well Clear (LoWC) & Near Midair Collisions (NMACs)

Instances of RA Non-Compliance

CRUISE SCENARIOS

Cruise Scenarios

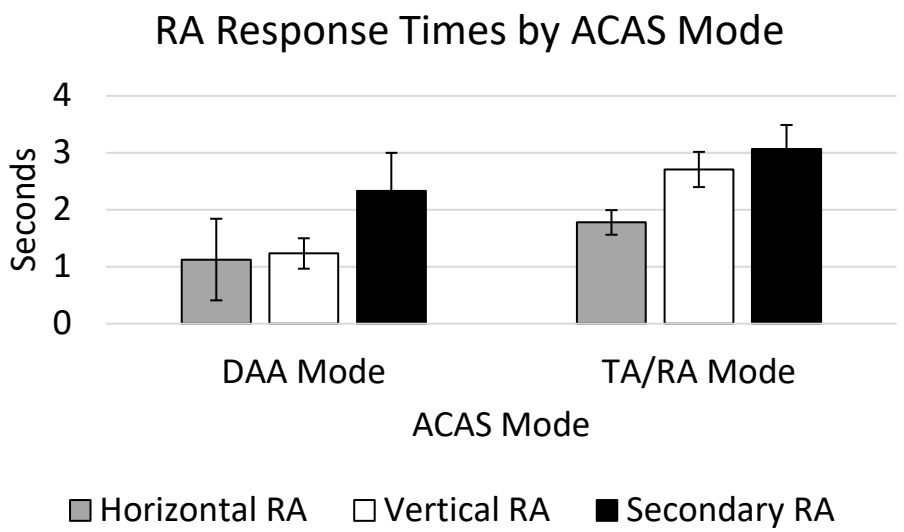
- Ownship parameters
  - Speed: 110 kts
  - Altitude: 500-1500ft MSL

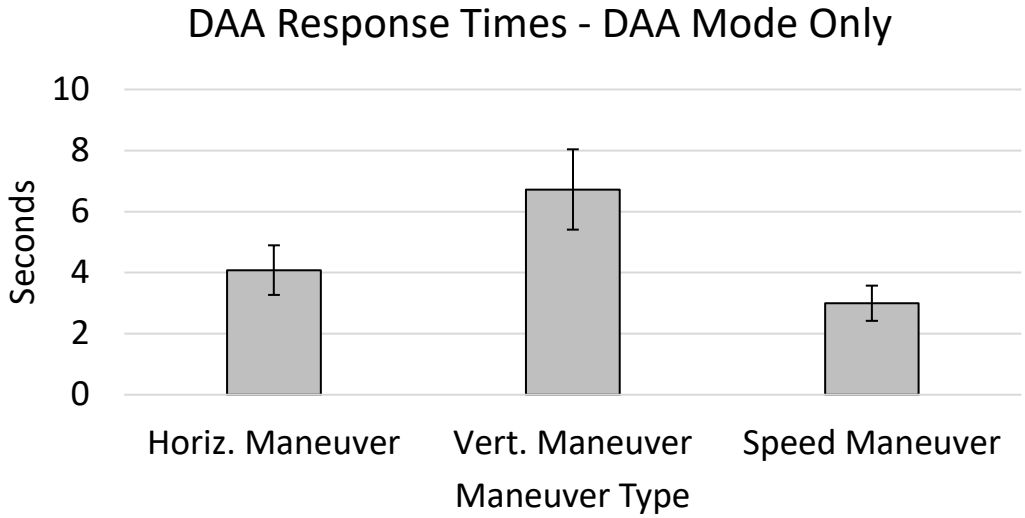
- ACAS Mode Distinctions:
  - TA/RA Mode: generating TAs & RAs; utilizing Descend RA inhibit starting at 750ft AGL
  - DAA Mode: generating all DAA & RA alert types; utilizing GPOA functionality

DAA & RA Response Times in Cruise

- TA/RA Mode
  - RA response times under 5 seconds

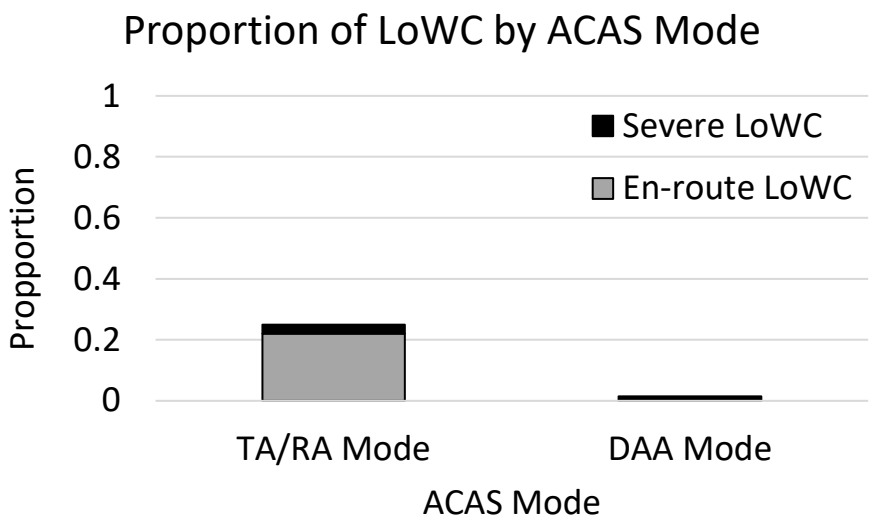
- DAA Mode
  - RA response times under 5 seconds
  - DAA response times all under 8 seconds
    - Reminder: no ATC interaction
  - DAA maneuver types:
    - **> 90%** of maneuvers against DAA Corrective alerts were multi-axis (horizontal + vertical)
    - **< 10%** of DAA maneuvers included a speed change





LoWC & NMACs in Cruise

- TA/RA Mode
  - NMACs: 0
  - En-Route LoWC: 15/60 (25%) / “Severe” LoWC: 2/60 (3%)
- DAA Mode
  - NMACs: 0
  - En-Route LoWC: 1/60 (1.5%) / “Severe” LoWC: 1/60 (1.5%)



	Horizontal Separation	Vertical Separation	modTau
En-Route LoWC	4000’	450’	35 seconds
“Severe” LoWC	4000’	450’	N/A
NMAC	500’	100’	N/A

RA Non-Compliance in Cruise

- *Non-Compliance = pilot ignored RA or maneuvered in different direction/dimension*

- TA/RA Mode: 11/60 total (18%)
  - 5 disregarded Level Off RA in favor of another maneuver because they felt Level Off was not appropriate
  - 3 leveled out of a Climb or Descend RA early because felt they had maneuvered sufficiently
  - 3 modified response due to proximity to terrain (e.g., stopped descend RA early)

- DAA Mode: 2/19 total (11%)
  - 1 initially descended for a Climb RA
  - 1 ignored RA because aircraft were diverging when it was issued

HOVER SCENARIOS

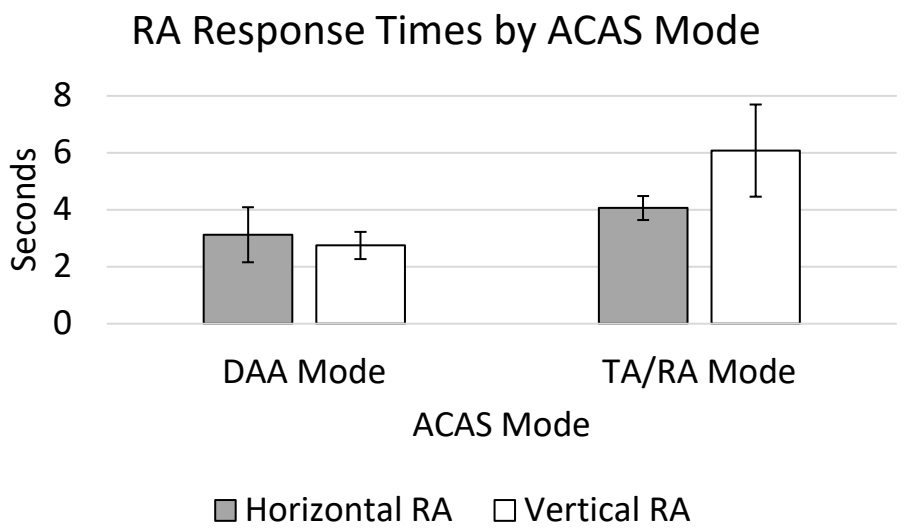
Hover Scenarios

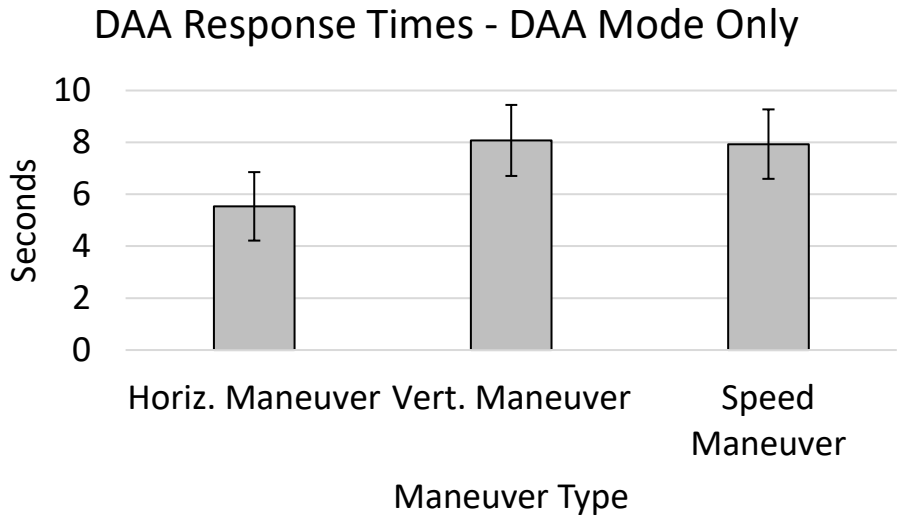
- Ownship parameters
  - Speed: 10 kts
  - Altitude: 500-1500ft MSL
  - Hover behavior: pilots trained to increase speed to at least 25kts when responding to RAs
    - Also required pilots to ‘disengage’ Hover mode (unique to NASA control scheme)

- ACAS Modes (same as Cruise)
  - TA/RA Mode: generating TAs & RAs; Descend RA inhibit starting at 750ft AGL
  - DAA Mode: generating all DAA & RA alert types; utilizing GPOA functionality

DAA & RA Response Times in Hover

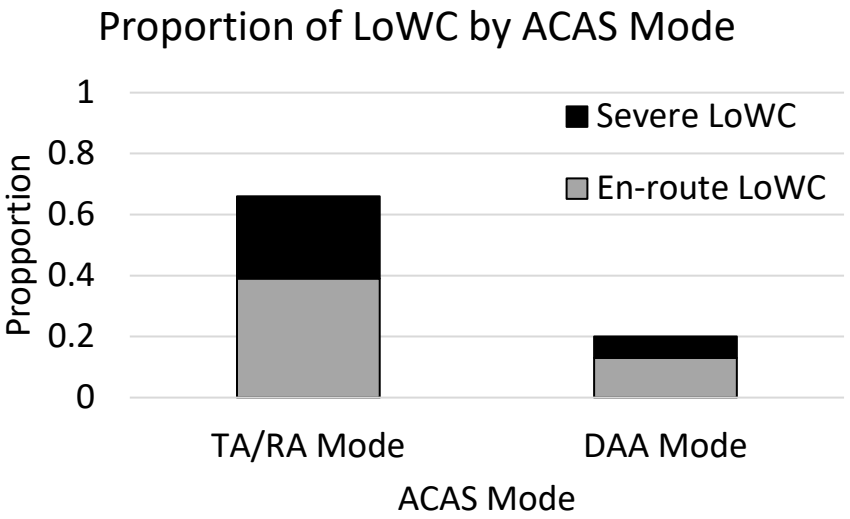
- TA/RA Mode
  - Horizontal RA response times < 5 seconds
  - Vertical RA response times 6 seconds
    - Requirement to disengage ‘hover mode’ slowed pilots down
- DAA Mode
  - RA response times < 5 seconds
  - DAA response times < 10 seconds
    - Reminder: no ATC interaction
  - DAA maneuver types:
    - Nearly all DAA maneuvers were in made in all 3 dimensions (horizontal, vertical, and speed)





LoWC & NMACs in Hover

- TA/RA Mode
  - NMACs: 0
  - En-Route LoWC: 40/60 (66%) / “Severe” LoWC: 16/60 (27%)
    - Additional time required to disengage and accelerate to 25kts (avg. 17 seconds)
    - 4 were stuck between an intruder above and terrain below
    - 2 lost well clear when returning to course



- DAA Mode
  - NMACs: 0
  - En-Route LoWC: 12/60 (20%) / “Severe” LoWC: 4/60 (7%)
    - Additional time required to disengage and accelerate to 25kts
    - 4 stuck between intruder above and terrain/obstacles below

	Horizontal Separation	Vertical Separation	modTau
En-Route LoWC	4000’	450’	35 seconds
“Severe” LoWC	4000’	450’	N/A
NMAC	500’	100’	N/A

RA Non-Compliance in Hover

- TA/RA Mode: 8/60 total (13%)
  - 3 climbed or descended during Level Off RA
  - 2 leveled out of a Climb RA early
  - 1 initially climbed for a Descend RA
  - 1 preferred climb over Left Turn RA

- DAA Mode: 15/35 total (43%)
  - 9 leveled out of a Descend RA early due to terrain
  - 4 climbed during Descend RA

APPROACH SCENARIOS

Approach Scenarios

- Ownship parameters
  - Speed: 70 kts (approach speed)
  - Altitude: ~1000ft MSL (starting)
  - Approach path: straight in, with 6° glide slope
  - Pilots were told to perform go-around if they decide to abandon the approach

- ACAS Modes
  - TA/RA Mode: TA-Only mode was manually engaged upon start of approach scenarios
  - DAA Mode: Preventive & Corrective alerts and horizontal RAs suppressed, only generating vertical RAs with, *per UAS DAA MOPS (DO-365B)*

Approach Configuration

TA/RA Mode

- *Traffic Advisory* (TA) issued first
  - Visual & aural alert (“Traffic, Traffic”)
  - Used to maneuver at pilots’ discretion - no maneuver guidance
  - Pilot can try to visually acquire traffic

- *Resolution Advisory* (RA) eventually issued
  - Visual & aural alert (e.g., “Climb, Climb”, “Turn Right, Turn Right”)
  - Vertical and/or horizontal guidance dictates how pilot maneuvers
  - Maneuver expected within 5 seconds

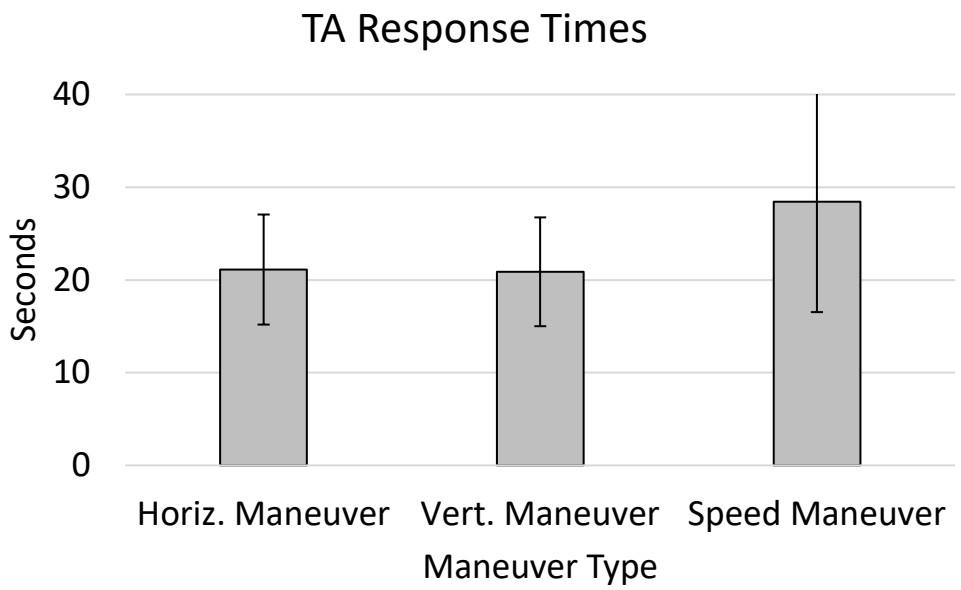
DAA Mode

- *DAA Corrective* alert issued first
  - Visual & aural alert (“Traffic, Avoid”)
  - Guidance “banding” used by pilot to determine if/how to maneuver
  - Airspeed, heading and vertical speed bands

- *Resolution Advisory* (RA) issued for terminal area collision avoidance separation volume
  - Only vertical directives are issued
  - Otherwise, presentation same as TA/RA Mode

DAA & RA Response Times on Approach

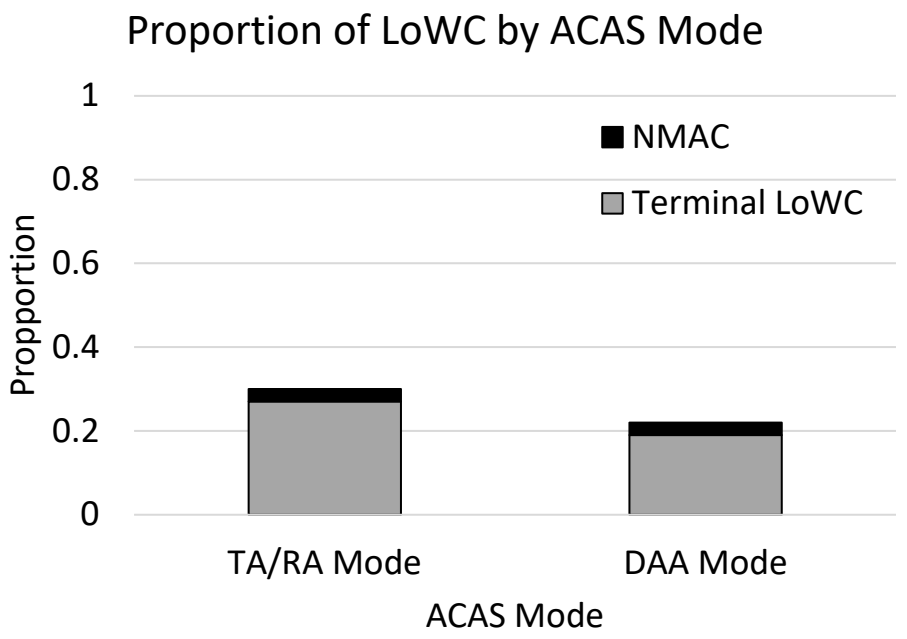
- TA/RA Mode
  - TA response times 20-30 seconds
    - ~10 seconds slower than DAA Corrective response times observed in Cruise and Hover



- DAA Mode
  - RA Response Times < 5 seconds

LoWC & NMACs on Approach

- TA/RA Mode
  - NMACs: 2/60 (3%)
    - Both pilots chose to maneuver after the intruder was visually acquired
  - Terminal Area LoWC : 18/60 (30%)
    - Split between pilots maneuvering too late or not at all
- DAA Mode
  - NMACs: 2/60 (3%)
    - Pilots complied with Level Off RA
  - Terminal Area LoWC: 13/60 (22%)
    - Generally complied with RAs that led to LoWC



	Horizontal Separation	Vertical Separation
Terminal Area LoWC	1500’	450’
NMAC	500’	100’

RA Non-Compliance on Approach

- TA/RA Mode: Pilots did not experience RAs
  - 6 cases where a pilot did not maneuver at all against the TA (only 2 pilots)
    - All were Terminal LoWC, but not NMACs

- DAA Mode: 11/60 total (18%)
  - 9 climbed or descended against a Level Off RA
  - 1 leveled out of Climb RA early

SUBJECTIVE RESULTS

Overall Feedback

General DAA Feedback

General RA Feedback

OWG-Related Questions

Overall Feedback

- No consistent differences in pilots' ratings of DAA vs TA/RA Mode
  - Half preferred DAA Mode, and half TA/RA Mode
- In Hover and Approach, pilots noted that fewer Level Off RAs and more Horizontal RAs would have led to higher rates of compliance/better performance
  - Pilots rated Xr as least effective in Hover encounters
- Alerting and guidance effective for maintaining sufficient separation (avg. 4.5 out of 5)
- Xr's DAA Mode useful in current-day, VFR rotorcraft operations (avg. 4.2 out of 5)

General DAA Feedback

- All stated that the presence of DAA banding affected their maneuver decisions
  - Made maneuvers easier (provided options & confirmed or corrected pilots' initial reactions)
  - Provided more situational awareness

- Most useful:
  - DAA aural cues (avg. 4.7 out of 5)
  - DAA vertical band (avg. 4.3 out of 5)
  - DAA heading band (avg. 4.2 out of 5)

- Less useful:
  - DAA text banners (avg. 3.8 out of 5)
  - DAA airspeed band (avg. 3.2 out of 5)

General RA Feedback

- 5 of 6 pilots found the 3° per second turn rate acceptable

- Even split on the ideal default vertical rate:
  - 3 of 6: 1000 ft/min
  - 3 of 6: 500 ft/min

- Most useful:
  - Horizontal RAs (avg. 4.6 out of 5)
  - Vertical RAs (avg. 4.5 out of 5)
  - Blended RAs (avg. 4.6 out of 5)

- Less useful
  - RA text banners (avg. 3.3 out of 5)

- Clear of conflict aural would have been useful (avg. 4 out of 5)

WRAP UP

Wrap Up

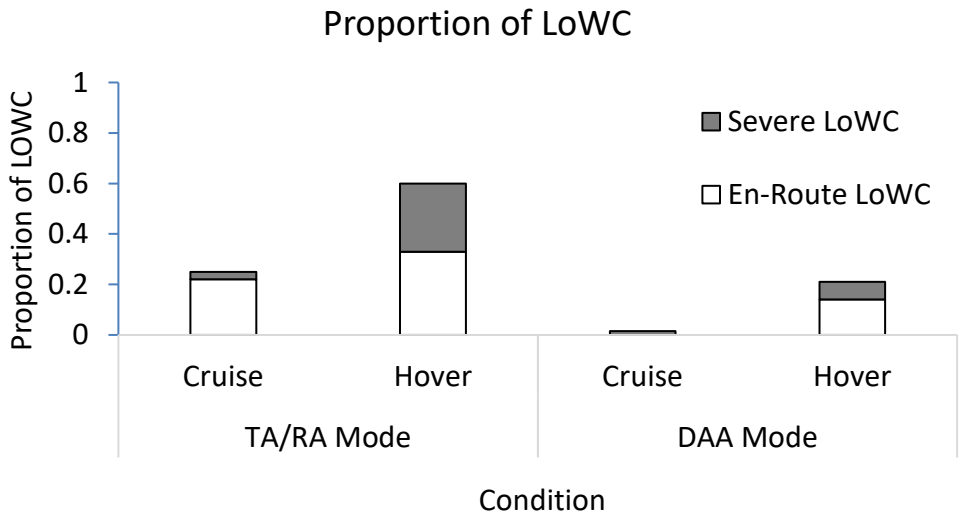
- Cruise
  - RA response times consistently under 5 seconds in both ACAS modes
  - DAA response times in the DAA Mode were especially fast (3-8 seconds)
    - Due to lack of ATC coordination and hands-on controls
  - 90% of DAA maneuvers were vertical + horizontal but *did not* include speed
  - "Severe" loss of well clear rare in both modes, but DAA Mode had far fewer En-Route LoWC

	TA/RA Mode	DAA Mode
En-Route LoWC	25%	1.5%
Severe LoWC	3%	1.5%

  - Pilot non-compliance in Cruise was primarily in response to:
    - Pilots disagreeing with Level Off RA commands
    - Pilots ending Descend RA maneuvers early due to terrain proximity

Wrap Up

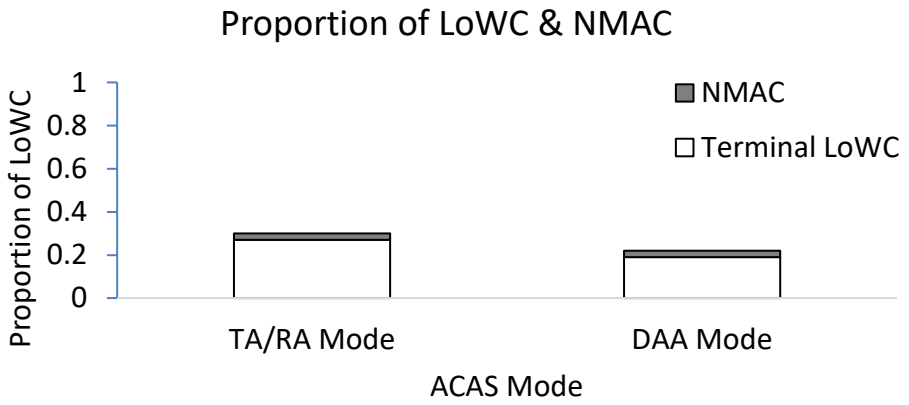
- Hover
  - Similar response times findings as in Cruise
  - Proportion of LoWC increased substantially in Hover relative to Cruise for *both* ACAS Modes
    - Result of extra time required to increase speed to 25+ knots



  - Pilot non-compliance in the terminal area was much more common for the DAA Mode
    - Result of a greater number of Descend RAs issued in DAA Mode compared to TA/RA Mode
    - Pilots felt they got too close to terrain and frequently leveled off/climbed while Descend RA was active

Wrap Up

- Terminal Area
  - Observed response times of 20-30 seconds against TAs in TA Only Mode
  - ACAS Mode had little effect on LoWC, despite no RAs being issued in TA/RA Mode
    - Difficulty of encounters partially to blame, but ineffective RA guidance led to LoWC and NMACs in multiple encounters (e.g., Level Off RAs against co-alt intruder)



  - Non-compliance in the DAA Mode was primarily due to pilots disagreeing with Level Off RAs

Overall

- Pilots rated ACAS as effective, especially in Cruise encounters

- Pilots rated the DAA Mode as useful in general but half said they would prefer to fly with the TA/RA Mode due to less perceived clutter
  - DAA airspeed guidance was rarely utilized and ranked as least effective element

- Pilots overall found RA guidance reasonable, however:
  - 1/2 felt default vertical rate should be 500fpm
  - Level Off RAs frequently led to 'non-compliance' in all phases of flight*
  - Descend RAs in DAA Mode (which utilized GPOA function) often brought pilots too close to terrain, resulting in numerous non-complies**

**Xr v3 will not issue Level Off RAs against terminal area intruders*

***Xr v3 will have increased sensitivity to/buffer against terrain/obstacles*

Next Steps

- Our next study will examine ACAS Xr in a live-flight environment

- Integration of Automated Systems (IAS) flight tests scheduled May-September 2023
  - Utilizing Sikorsky Autonomous Research Aircraft (SARA; an S-76B)
  - Similar encounter set – Cruise, Hover, and Approach – against ADS-B Out intruder
  - Automating the RA maneuvers with onboard pilot monitoring

Questions?