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Piloted Simulation Based Assessment of Simplified Vehicle Operations for Urban Air Mobility

Dr. Imon Chakraborty

Assistant Professor & VSDDL Director

Department of Aerospace Engineering
Auburn University

Email: imon@auburn.edu

Webcast for the
NASA Engineering and Safety Center Flight Mechanics Technical Discipline Team

Dr. Imon Chakraborty

Dr. Imon Chakraborty
Assistant Professor
Department of Aerospace Engineering
Auburn University
(August 2018 – present)

Research Engineer II
School of Aerospace Engineering
Georgia Institute of Technology
(Jan 2016 – July 2018)

Ph.D., Aerospace Engineering (Dec 2015)
Georgia Institute of Technology

M.S., Aerospace Engineering (Jul 2011)
Georgia Institute of Technology

B.Tech., Mechanical Engineering (May 2009)
National Institute of Technology Trichy, India

Professional Memberships

- AIAA Associate Fellow (class of 2023)
- AIAA Aircraft Design Technical Committee
- AIAA Modeling & Simulation Technologies Technical Committee

Aviation

- Private Pilot, Airplane, Single-Engine, Land (Mar 2013 – present)
- Airplane owner (Jan 2022 – present)

Email: imon@auburn.edu
Web: www.vsddl.com

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Vehicle Systems, Dynamics, and Design Laboratory (VSDDL)

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- VSDDL research focuses on sizing, performance and stability & control analysis, and flight simulation
- Developed the PEACE aircraft sizing framework, applicable to vehicles using wing-borne, rotor-borne, and buoyant lift or combinations thereof
- Developed the MADCASP S&C analysis and flight simulation framework with NASA funding; aimed at analysis of novel configurations
- Developed cockpit flight simulators to enable human-in-the-loop flight simulation research for Advanced Air Mobility (AAM) concepts

VSDDL

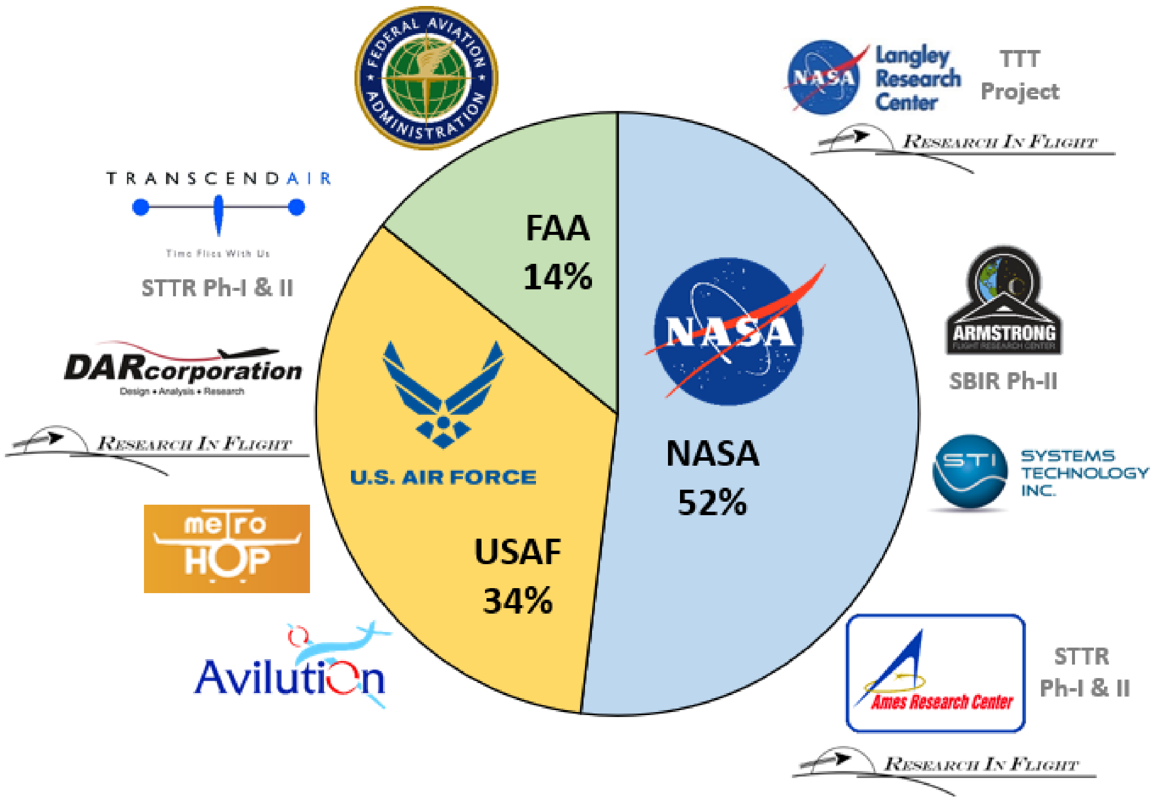
"Vehicle"
- Conventional & Unconventional

"Systems"
- Sizing & analysis of key systems

"Dynamics"
- Flight simulation, S&C analyses

"Design"
- Capture impacts of above on vehicle design

Cumulative external funding flowing to VSDDL @ AU from Aug 2018 – present: $1.5M+



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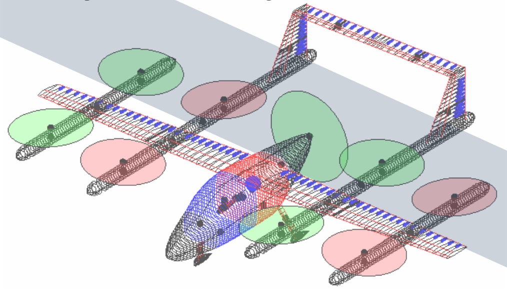
VSDDL Vision: An R&D "Pipeline" for Next-Gen Concepts

Vehicle sizing, performance analysis, and optimization

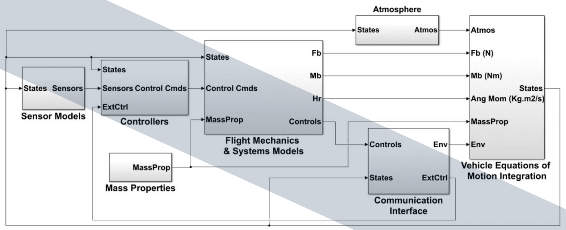


Parametric Energy-based Aircraft Configuration Evaluator (PEACE)

Developed internally at VSDDL; aimed at facilitating sizing and performance analysis of novel aircraft and propulsion system architectures

Webcast #1, Feb 22, 2023, 1:00 pm EST

S&C analysis, flight control system architecture design & optimization

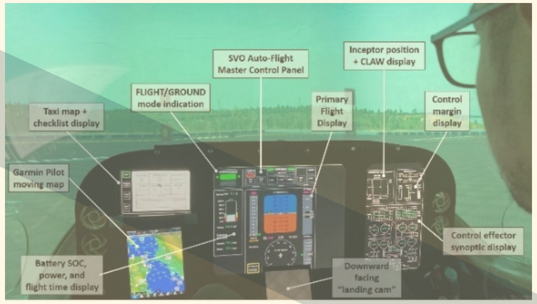


Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP)

Developed with funding from NASA Langley Research Center under Transformational Tools and Technologies (TTT) Project

Webcast #2, Mar 1, 2023, 1:00 pm EST

Flight simulation model development; human-in-the-loop simulations

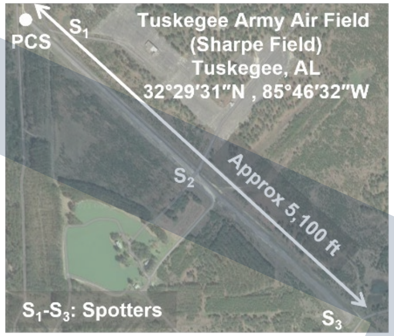


VSDDL Flight Simulators

Developed in-house for studying Simplified Vehicle Operations (SVO)

Webcast #3, Mar 8, 2023, 1:00 pm EST

Subscale prototype development & piloted flight tests



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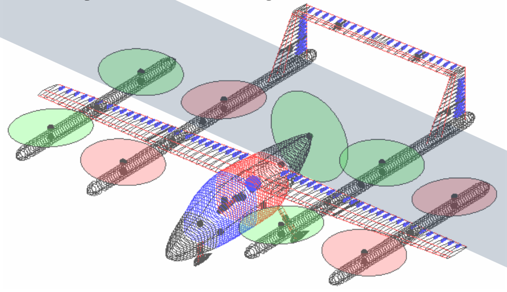
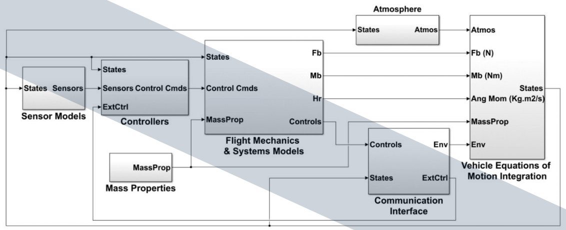
VSDDL Vision: An R&D "Pipeline" for Next-Gen Concepts

Vehicle sizing, performance analysis, and optimization



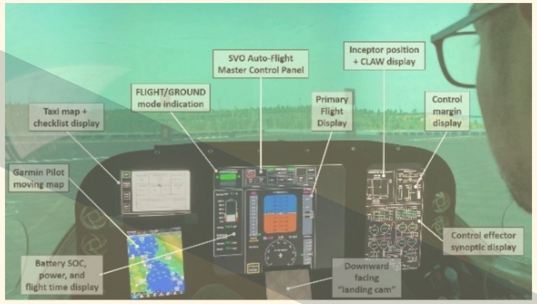
Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0398

S&C analysis, flight control system architecture design & optimization



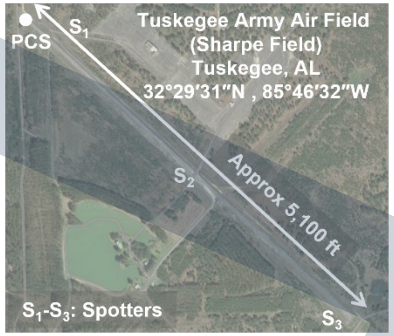
Comer, A. and Chakraborty, I., **"Total Energy Flight Control Architecture Optimization for a Lift-Plus-Cruise Aircraft,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0399

Flight simulation model development; human-in-the-loop simulations



Chakraborty et al., **"Flight Simulation Based Assessment of Simplified Vehicle Operations for Urban Air Mobility,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0400

Subscale prototype development & piloted flight tests



Funding Acknowledgment – Federal Aviation Administration (FAA)

- "Flight Simulation-Driven Research into Simplified Vehicle Operations for Urban Air Mobility"
  - FAA Aviation Research Grants Program, Cooperative Agreement #692M152140004
  - Period of performance: August 18, 2021 – Jan 31, 2023
  - PI: Dr. Imon Chakraborty

- Students supported
  - Anthony Comer
  - Aashutosh Aman Mishra
  - Rajan Bhandari
  - Stefanus Harris Putra

- FAA Technical Points of Contact
  - Dave Sizoo
  - Ross Schaller
  - Robert McGuire
  - Dan Dellmyer

- **Recent SCITECH 2023 paper:** Chakraborty, I., Comer, A., Bhandari, R., Putra, S., Mishra, A., Schaller, R., Sizoo, D., and McGuire, R., *"Piloted Simulation Based Assessment of Simplified Vehicle Operations for Urban Air Mobility,"* AIAA SCITECH 2023 Forum, National Harbor, MD & online, 23-27 January, 2023, AIAA-2023-0400

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Goals and Objectives of the Project

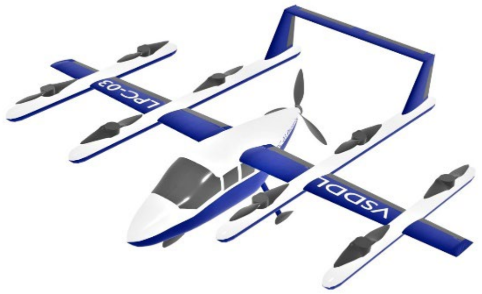
- **Simplified Vehicle Operations:** the use of automation/autonomy and coupled with human factors best practices, to reduce the quantity of trained knowledge, skills, abilities, and experience that the pilot or operator of an aircraft must acquire to operate safely and proficiently

- Achieving this requires a coordinated and holistic approach towards the design of:
  - Flight control laws
  - Inceptors
  - Cockpit displays

- The goal of this FAA-funded project was to study the following in the context of Urban Air Mobility (UAM)
  - Total Energy Control System (TECS) based flight control laws
  - Two different inceptor designs
  - Simplified cockpit displays

- A lift-plus-cruise (LPC) vertical takeoff and landing (VTOL) configuration was considered
  - The same LPC configuration that was considered in Webcasts 1 and 2

“Blue Sim” and “Red Sim” – Used to Support this Project

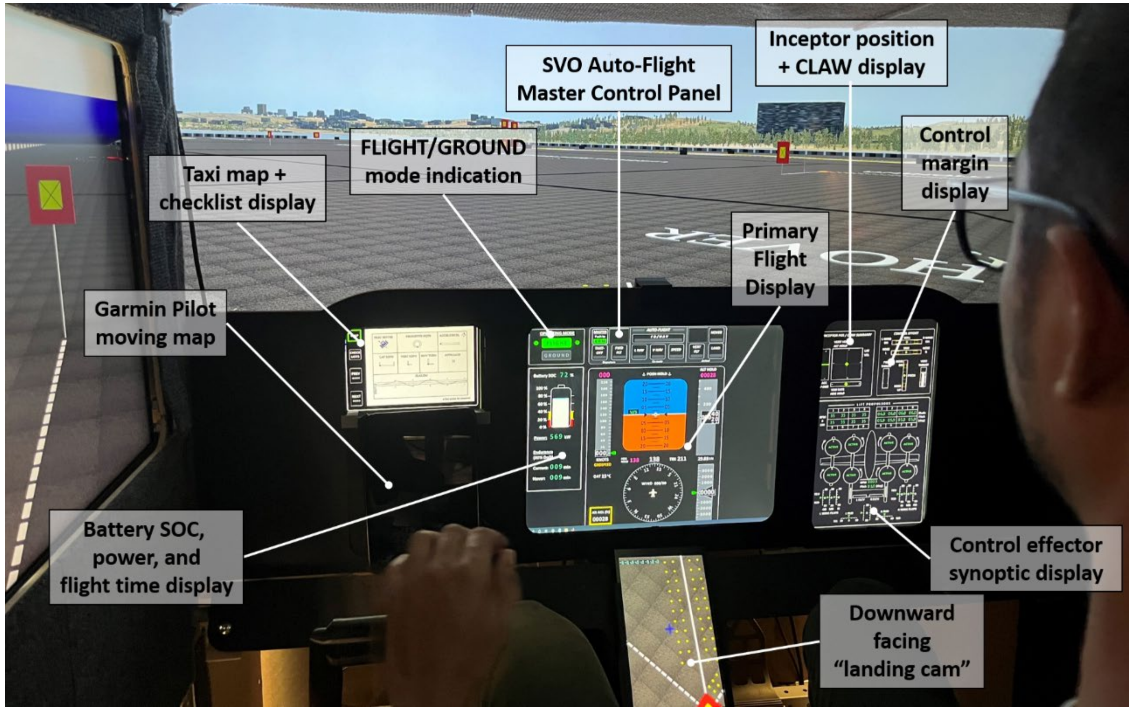


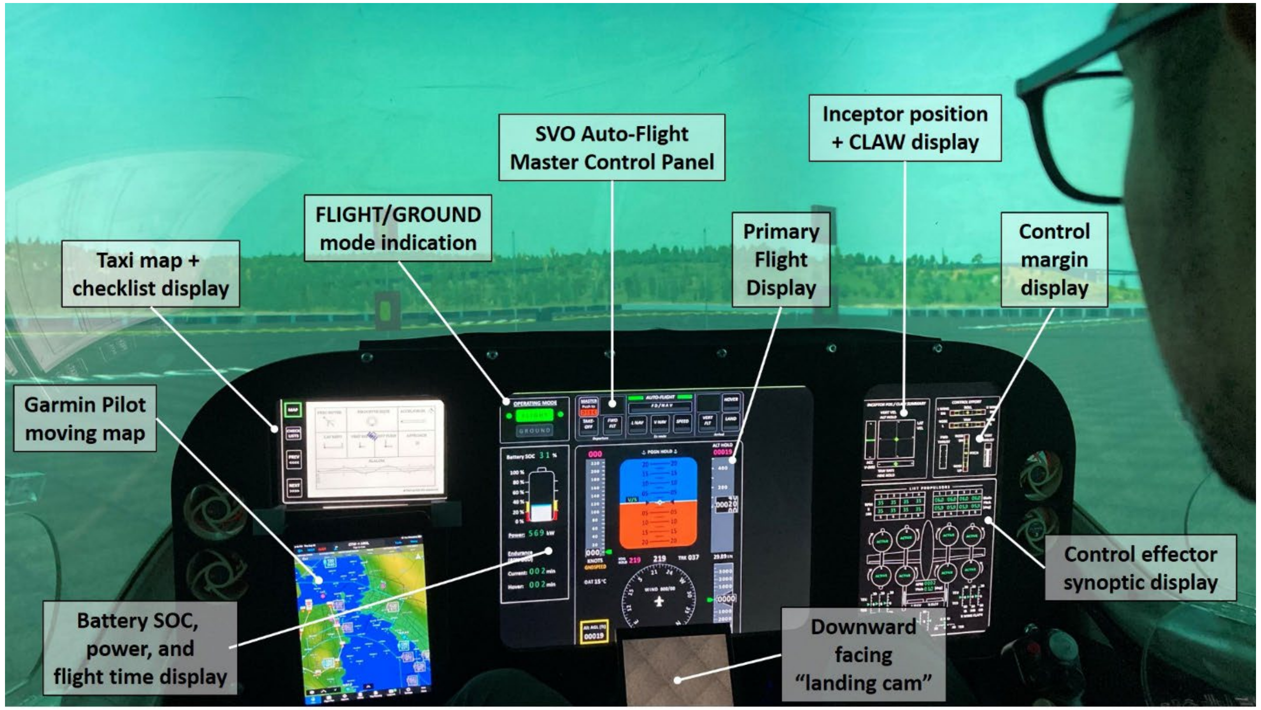
“Blue Sim”
VSDDL Flight Sim #1

“Red Sim”
VSDDL Flight Sim #3

Identical: Aircraft model, cockpit display elements, simulation tasks

Different: Inceptor designs and inceptor-to-command mappings

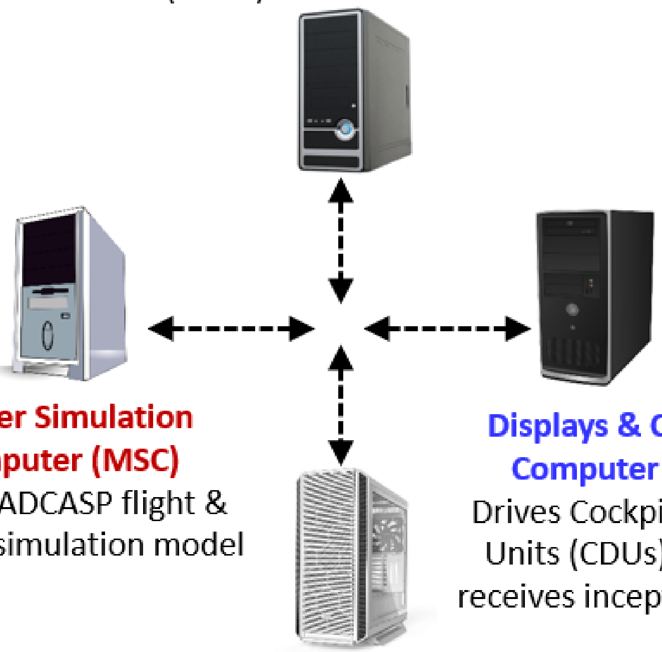




Flight Simulator Systems Architecture

https://www.vsddl.com/flight-simulators/

Image Generation Computer(s) (IGC)
Drive Visual Display Units (VDUs) for external visuals

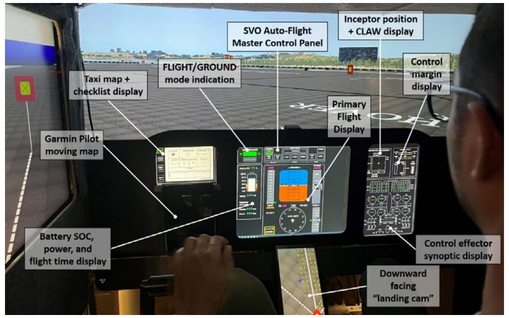


Master Simulation Computer (MSC)
Runs MADCASP flight & systems simulation model

Displays & Controls Computer (DCC)
Drives Cockpit Display Units (CDUs), audio; receives inceptor inputs

Control Loading Computer (CLC)
Drives Control Loading Units (CLUs)

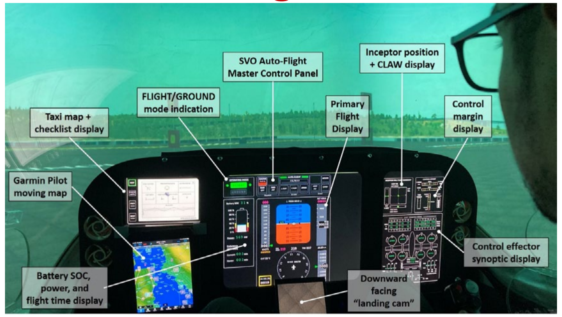
"Blue Sim"
VSDDL Flight Sim #1



Front: 1 large flat screen
Each side: 2 smaller flat screens

Center: 13.4"w x 10.7"h 1920 x 1080 touch
L & R: 21.3"w x 12.3"h 1920 x 1080 touch
Landing cam: 3.4"w x 6.1"h 1080 x 1920
iPad Mini, Garmin Pilot moving map

"Red Sim"
VSDDL Flight Sim #3



5 overhead projectors casting on to 16-ft diameter, 270 deg horizontal FOV cylindrical screen

Center: 13.4"w x 10.7"h 1920 x 1080 touch
L & R: 6.5"w x 11.6"h 1080 x 1920 touch
Landing cam: 3.4"w x 6.1"h 1080 x 1920
iPad Mini, Garmin Pilot moving map

Not present in either Blue Sim or Red Sim

Lift-Plus-Cruise (LPC) Urban Air Mobility (UAM) Concept with Electrified Propulsion

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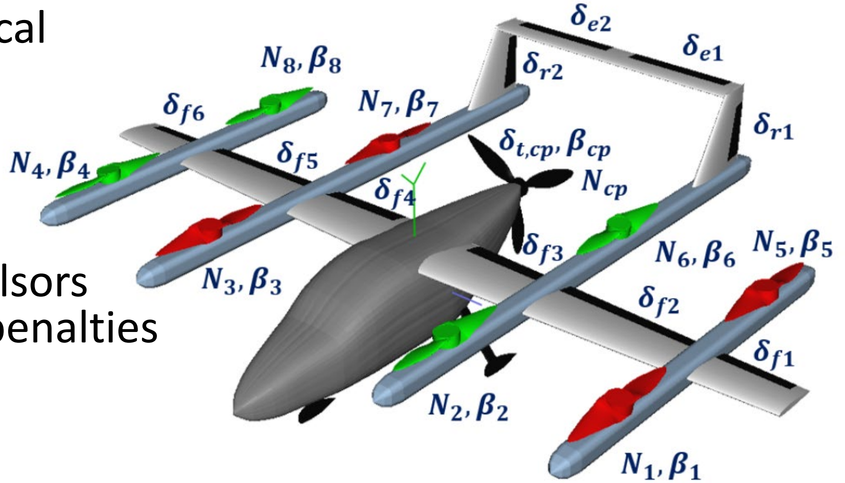
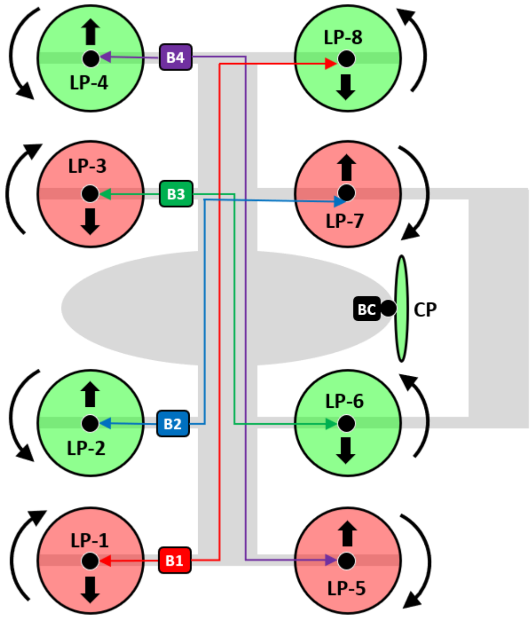
- "Lift-Plus-Cruise" – separate propulsors for vertical thrust ("lift") and forward thrust (for cruise)
  - Advantage: Simpler aerodynamically than vectored thrust (tilt-wing and tilt-rotor)
  - Disadvantage: In cruise flight, the lift propulsors are inactive, thus "dead-weight" and drag penalties
- **Forward flight mode:**
  - Conventional control surfaces in forward flight mode:
  - Flaperons (roll), elevators (pitch), rudders (yaw)
- **Vertical flight mode:**
  - **Roll control:** differential blade pitch between left- and right-side lift rotors
  - **Pitch control:** differential blade pitch between lift rotors ahead of and aft of wing
  - **Yaw control:** differential blade pitch between clockwise and anti-clockwise turning rotors (rotors are tilted inward/outward as indicated by arrows)



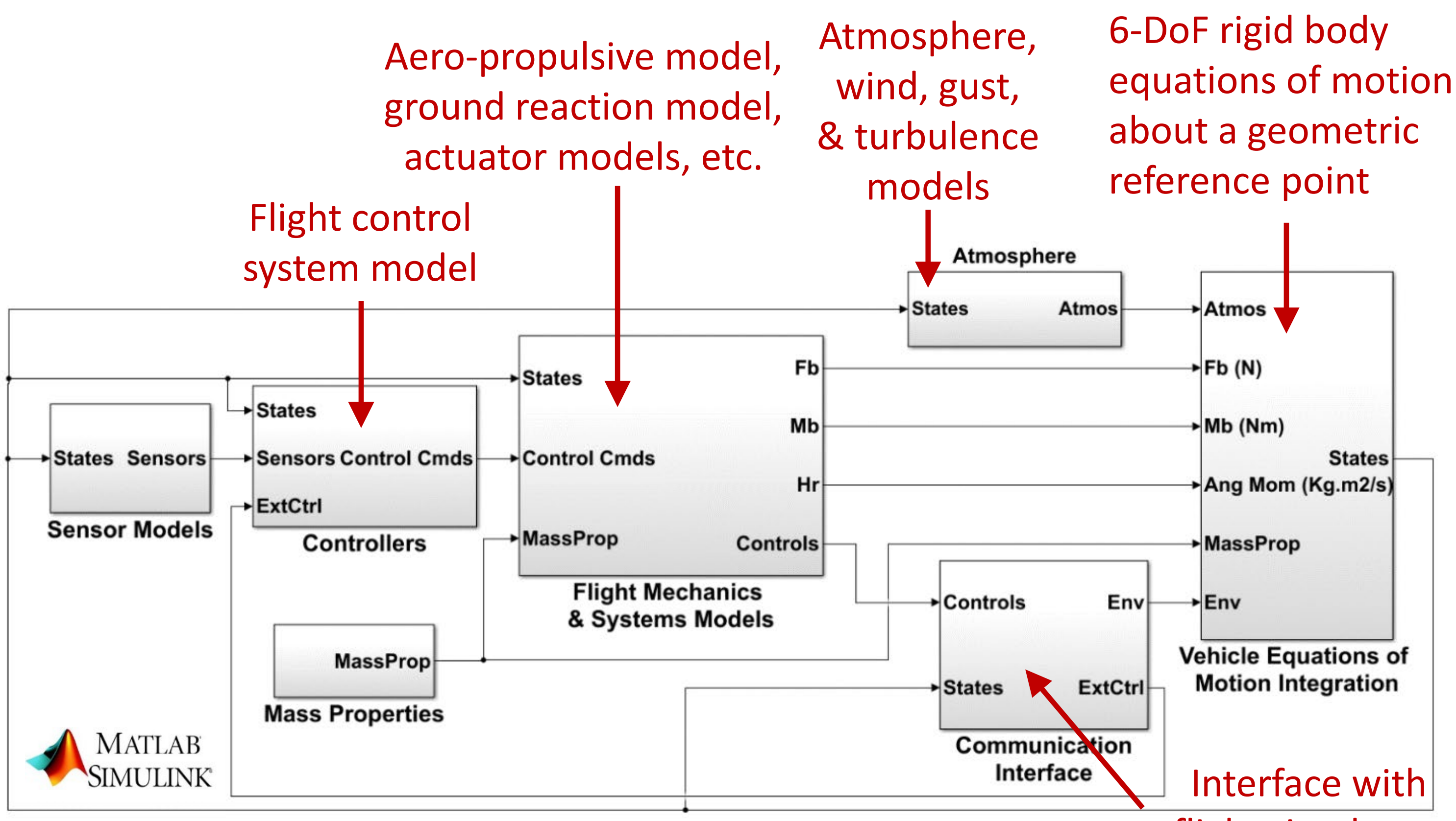


#	Symbol	Description	Unit
1-3	$\delta_{f1}, \delta_{f2}, \delta_{f3}$	Flaperon, left wing, out-/mid-/inboard	deg
4-6	$\delta_{f4}, \delta_{f5}, \delta_{f6}$	Flaperon, right wing, in-/mid-/outboard	deg
7, 8	δ_{e1}, δ_{e2}	Left, right elevator	deg
9, 10	δ_{r1}, δ_{r2}	Left, right rudder	deg
11	$\delta_{t,cp}$	Cruise propeller throttle setting	–
12	β_{cp}	Cruise propeller pitch	deg
13	N_{cp}	Cruise propeller RPM	RPM
14-21	$N_1 - N_8$	Lift propeller RPMs	RPM
22-29	$\beta_1 - \beta_8$	Lift propeller pitch	deg

MADCASP S&C Analysis and Flight Simulation Framework

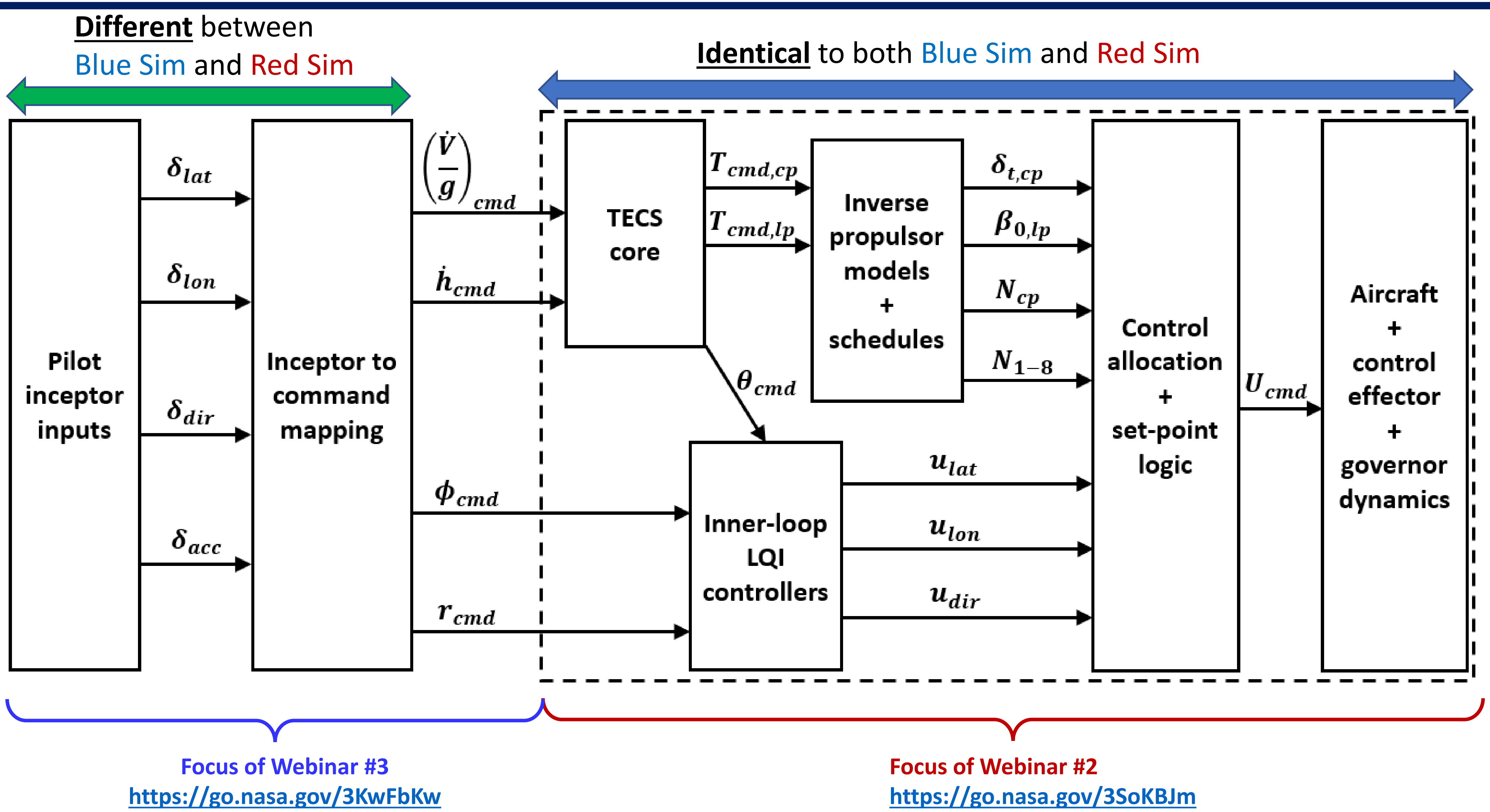
- Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP)
  - MATLAB/Simulink-based S&C analysis and flight simulation framework
  - Developed with NASA LaRC funding under Transformational Tools and Technologies (TTT) project: "Modular Generalized Framework for Assessing Aircraft Aero-Propulsive, Stability, and Control Characteristics", 80LARC19C0013 (Jan '19 – Dec '21)

- Trim analysis: Formulated as generalized constrained minimization problem
- Dynamic stability analysis:
  - Numerical linearization of model
  - eigenvalue problem on linearized models
- Integrates with flight simulators
  - Pilot-in-the-loop flight simulation
- Can input PEACE vehicle definition output
- Can use multiple forms of aero-propulsive performance models (APPM's)



Top-level of MADCASP Simulink framework

Flight Control System Architecture for LPC-03



Primary Flight Display (PFD) – Common to Both Simulators

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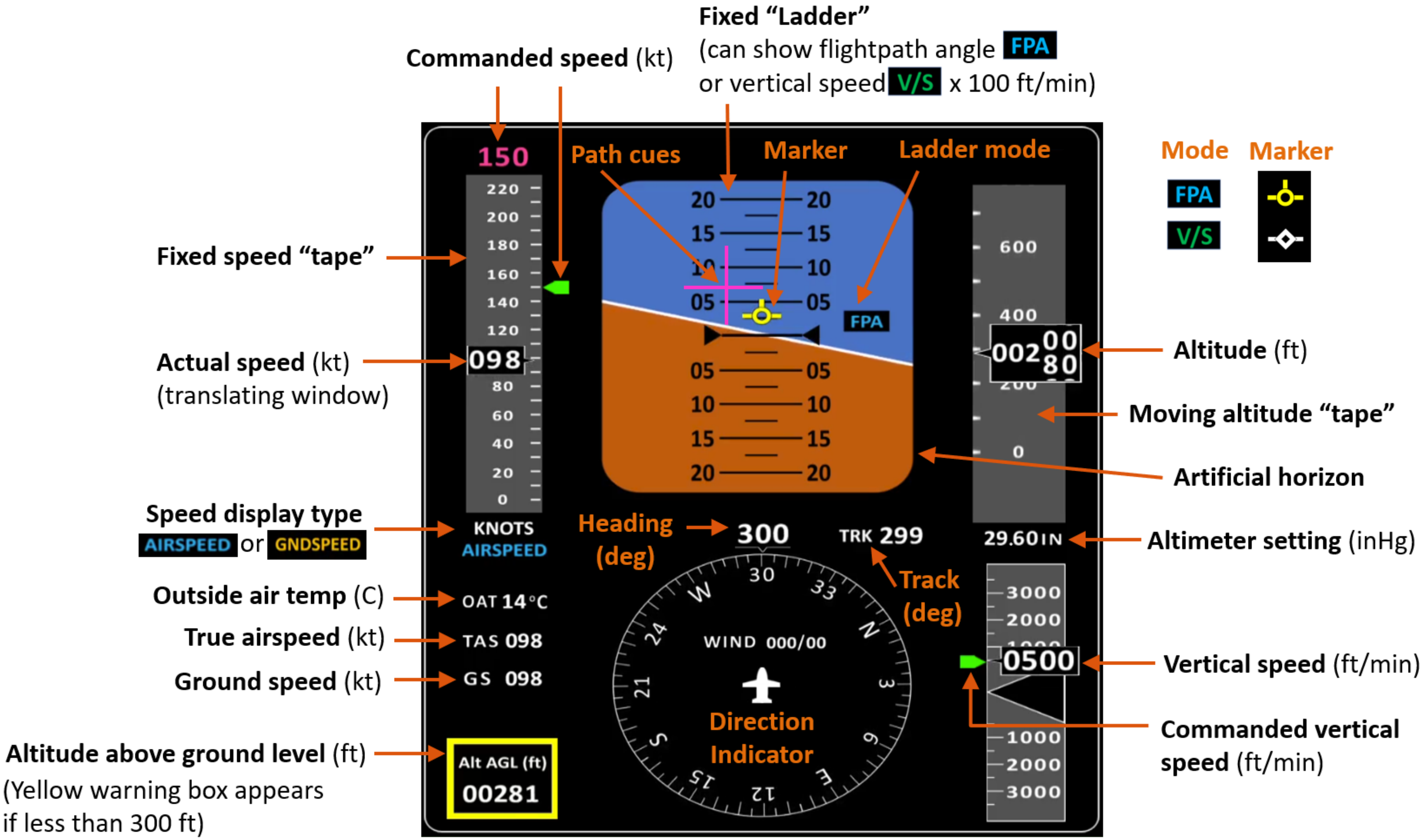
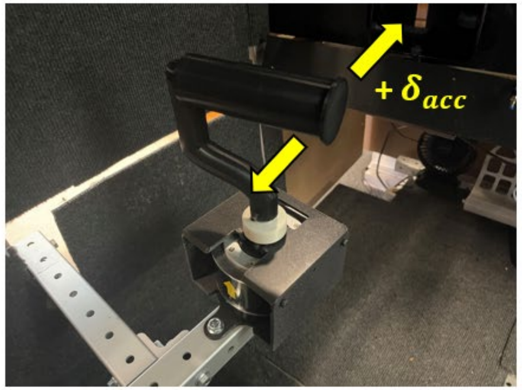


Airplane-Centric (AC) and Helicopter-Centric (HC) Inceptor Designs

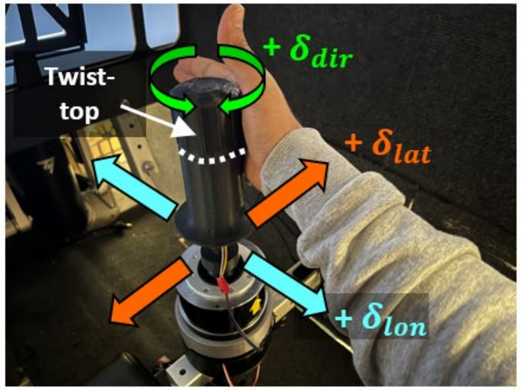
- Airplane-Centric (AC) inceptor scheme was installed in Blue Sim; Helicopter-centric (HC) was installed in Red Sim - schemes differed in physical inceptor designs and also inceptor-to-command mappings

Blue Sim

Airplane-Centric
Left Hand Inceptor (AC-LHI)

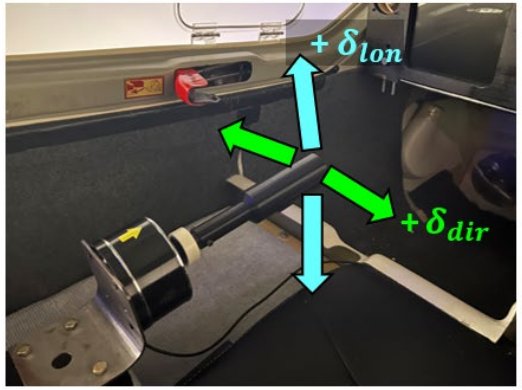


Airplane-Centric
Right Hand Inceptor (AC-RHI)

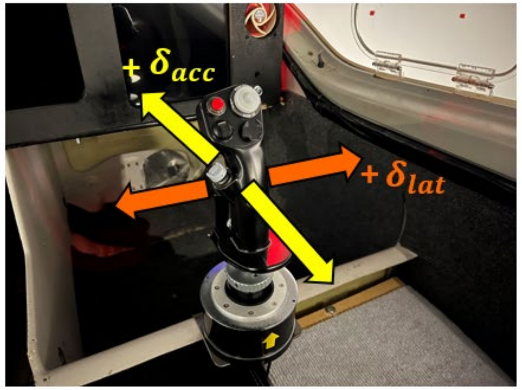


Red Sim

Helicopter-Centric
Left Hand Inceptor (HC-LHI)



Helicopter-Centric
Right Hand Inceptor (HC-RHI)



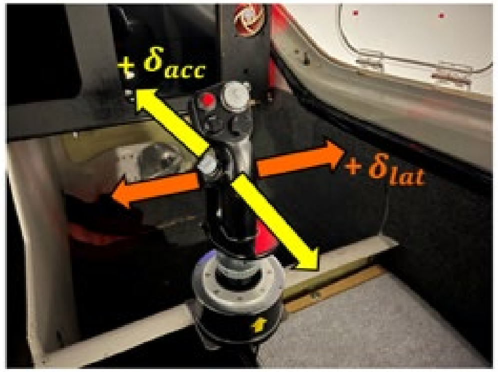
Input (symbol)	Mode	Blue Sim (AC Setup)	Red Sim (HC Setup)
Lateral (δ_{lat})		RHI side-to-side	RHI side-to-side
	VFM	Lateral velocity cmd	Bank angle cmd
	FFM	Roll rate cmd / bank hold	Bank angle cmd
Longitudinal (δ_{lon})		RHI fore-aft	LHI up-down
	VFM	Altitude rate cmd / Altitude hold	Altitude rate cmd / Altitude hold
	FFM	FPA rate cmd / FPA hold	Altitude rate cmd / Altitude hold
Directional (δ_{dir})		RHI twist	LHI side-to-side
	VFM	Heading rate cmd / Heading hold	Heading rate cmd / Heading hold
	FFM	Steady track sideslip	Steady track sideslip
Acceleration (δ_{acc})		LHI fore-aft	RHI fore-aft
	VFM	Speed rate cmd / Speed decay / Position hold	Speed rate cmd / Speed decay / Position hold
	FFM	Speed rate cmd / Speed hold	Speed rate cmd / Speed hold

Lateral Axis (δ_{lat})

- In both Blue Sim and Red Sim, the right-hand inceptor (RHI) left/right motion generates δ_{lat}
- **Red Sim**
  - δ_{lat} generates a bank angle command, $\frac{\phi_{cmd}}{\delta_{lat}}(s) = \frac{\phi_{cmd,max}}{\tau_{lat}s+1}$
  - No mode blend between vertical flight mode (VFM) and forward flight mode (FFM)
  - The maximum bank angle is limited based on airspeed.
- **Blue Sim**
  - In VFM, δ_{lat} generates a lateral velocity command, $\frac{v_{cmd}}{\delta_{lat}}(s) = \frac{v_{cmd,max}}{\tau_{lat}s+1}$
    - Proportional-integral (PI) control on lateral velocity error is used to generate bank command $\phi_{cmd,VFM}$
  - In FFM, δ_{lat} generates a roll rate command, $\frac{\dot{\phi}_{cmd,0}}{\delta_{lat}}(s) = \frac{\dot{\phi}_{cmd,max}}{\tau_{lat}s+1}$
    - Artificial "dihedral stability" term $\dot{\phi}_{cmd,dih} = -K\phi$ is added for $|\phi| > 45°$ and $|\phi| < 10°$
    - Roll rate command is integrated to yield bank angle command for FFM, $\phi_{cmd,FFM}$
  - Net bank angle command
    - $\phi_{cmd} = \zeta_{lat}\phi_{cmd,VFM} + (1 - \zeta_{lat})\phi_{cmd,FFM}$
    - Washout parameter ζ_{lat} is = 1 below 40 knots, = 0 above 50 knots, and has linear wash-out

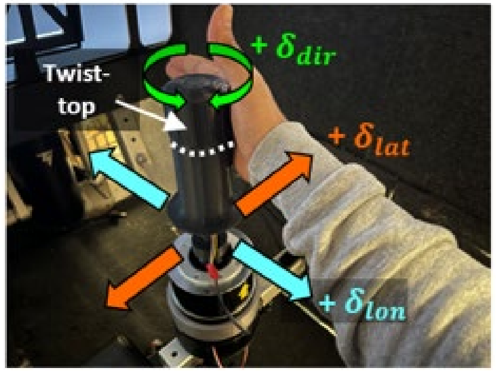
Red Sim

Helicopter-Centric
Right Hand Inceptor (HC-RHI)



Blue Sim

Airplane-Centric
Right Hand Inceptor (AC-RHI)



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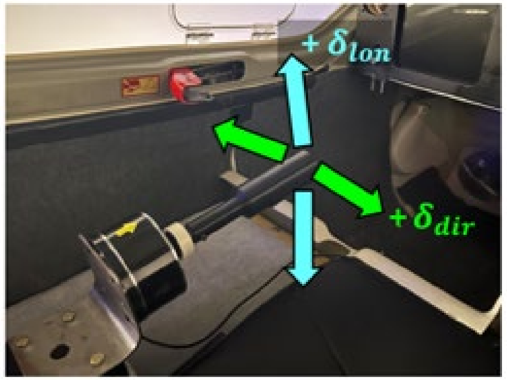
Longitudinal Axis ($\boldsymbol{\delta_{lon}}$)

- **Red Sim (LHI up/down)**
  - δ_{lon} generates a vertical velocity (height rate) command, $\frac{\dot{h}_{cmd}}{\delta_{lon}}(s) = \frac{\dot{h}_{cmd,max}}{\tau_{lon}s+1}$
  - No mode blend between vertical flight mode (VFM) and forward flight mode (FFM)
- **Blue Sim (RHI fore/aft)**
  - In VFM, δ_{lon} generates a vertical velocity (height rate) command, $\frac{\dot{h}_{cmd,VFM}}{\delta_{lon}}(s) = \frac{\dot{h}_{cmd,max}}{\tau_{lon}s+1}$
  - In FFM, δ_{lon} generates a FPA rate command, $\frac{\dot{\gamma}_{cmd}}{\delta_{lon}}(s) = \frac{|\dot{\gamma}_{cmd,lim}(V)|}{\tau_{lon}s+1}$
    - Max FPA rate command (FPARC) limited by load factor
    - FPARC is integrated to yield FPA command, γ_{cmd}. Response type is FPARC/FPAH
    - Corresponding vertical velocity command in FFM, $\dot{h}_{cmd,FFM} = V \sin\gamma_{cmd}$
  - Net vertical velocity command
    - $\dot{h}_{cmd} = \zeta_{lon}\dot{h}_{cmd,VFM} + (1-\zeta_{lon})\dot{h}_{cmd,FFM}$
    - Washout parameter ζ_{lon} is = 1 below 140 knots, = 0 above 150 knots, with linear wash-out

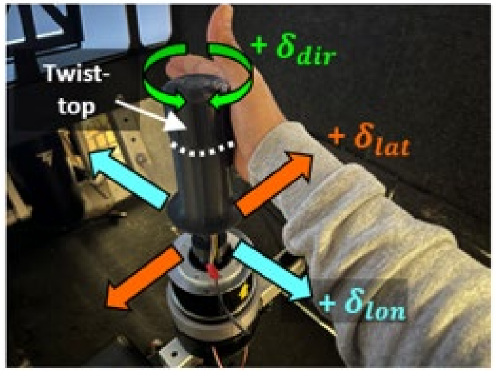
Red Sim

Helicopter-Centric
Left Hand Inceptor (HC-LHI)



Blue Sim

Airplane-Centric
Right Hand Inceptor (AC-RHI)



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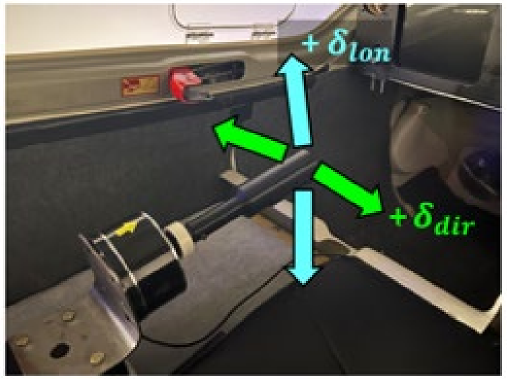
Directional Axis (δ_{dir})

- **Red Sim: LHI left/right**
- **Blue Sim: RHI twist left/right**
- Same inceptor-to-command mapping for both simulators
- In VFM, δ_{dir} generates a yaw rate command, $\frac{r_{cmd}}{\delta_{dir}}(s) = \frac{r_{cmd,max}}{\tau_{dir}s+1}$
- In FFM, δ_{dir} generates a sideslip command, $\frac{\beta_{cmd}}{\delta_{dir}}(s) = \frac{\beta_{cmd,max}}{\tau_{dir}s+1}$
  - If no inceptor input ($\delta_{dir} = 0$), yaw rate command $r_{cmd,FFM} = \frac{g}{V}\cos\gamma\sin\phi_{cmd} - K_{n_y}n_y$
    - Attempts to achieve coordinated flight (lateral acceleration $n_y = 0$)
  - When there is an inceptor input ($\delta_{dir} = 0$),
    yaw rate command $r_{cmd,FFM} = \frac{g}{V}\cos\gamma\sin\phi_{cmd} - K_{\beta}(\beta_{cmd} - \beta)$
- Net yaw rate command
  - $r_{cmd} = \zeta_{dir}r_{cmd,VFM} + (1-\zeta_{dir})r_{cmd,FFM}$
  - Washout parameter ζ_{dir} is = 1 below 40 knots, = 0 above 50 knots, with linear wash-out

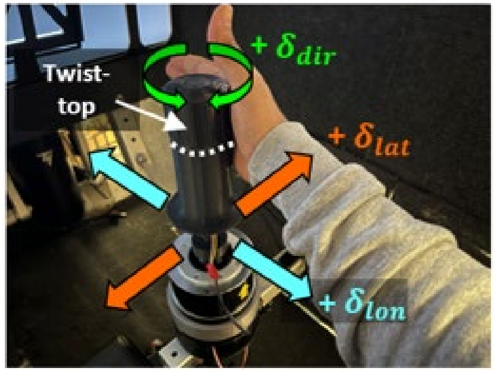
Red Sim

Helicopter-Centric
Left Hand Inceptor (HC-LHI)



Blue Sim

Airplane-Centric
Right Hand Inceptor (AC-RHI)



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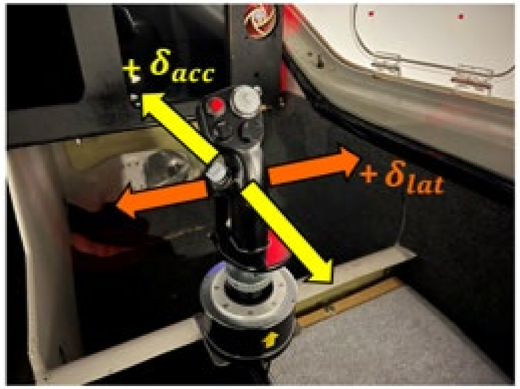
Acceleration Inputs ($\boldsymbol{\delta_{acc}}$)

- **Red Sim: RHI fore/aft**
- **Blue Sim: LHI fore/aft**
- Same inceptor-to-command mapping for both simulators
- In VFM, δ_{acc} generates an acceleration command, $\frac{a_{cmd,0}}{\delta_{acc}}(s) = \frac{a_{max}}{\tau_{acc}s+1}$
  - Added to this is a velocity dissipation effect at low speeds, $a_{diss} = -K_{diss}|V|\,\mathrm{sgn}(V)$
  - Dissipates the velocity to zero if inceptor is centered
  - Net VFM acceleration command is $a_{cmd,VFM} = a_{cmd,0} + a_{diss}$
- In FFM, δ_{acc} increments/decrements the commanded velocity, $\frac{\dot{V}_{cmd}}{\delta_{acc}}(s) = \frac{K_{\dot{V}}\,g}{\tau_{acc}s+1}$
  - This is integrated to generate commanded velocity V_{cmd}
  - FFM acceleration command synthesized as $a_{cmd,FFM} = K_V(V_{cmd} - V)$
- Net acceleration command
  - $(\dot{V}/g)_{cmd} = \zeta_{acc}a_{cmd,VFM} + (1-\zeta_{acc})a_{cmd,FFM}$
  - Washout parameter ζ_{acc} is = 1 below 25 knots, = 0 above 35 knots, with linear wash-out

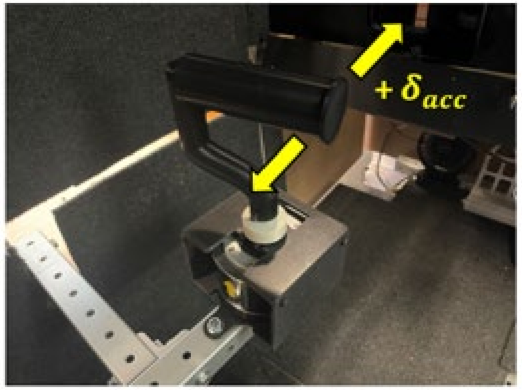
Red Sim

Helicopter-Centric
Right Hand Inceptor (HC-RHI)



Blue Sim

Airplane-Centric
Left Hand Inceptor (AC-LHI)



Altitude Hold, Heading/Track Hold, and Position Hold

POSN HOLD:

- Engaged when all inceptors are centered & forward and lateral velocities below thresholds
- Disengaged by $\delta_{lat}, \delta_{lon}$, or δ_{acc} inputs

ALT HOLD:

- Engaged when $\delta_{lon} = 0$ and vertical velocity magnitude less than a threshold
- Disengaged by δ_{lon} inceptor input
- Altitude increments of 1 ft in VFM and 50 ft in FFM

HDG HOLD & TRK HOLD:

- HDG HOLD engaged if directional input $\delta_{dir} = 0$ & yaw rate below threshold & speed < 40 knots
- TRK hold engaged if lateral input $\delta_{lat} = 0$ and bank angle below threshold & speed > 70 knots
- HDG HOLD disengaged by δ_{dir} input. TRK HOLD disengaged by δ_{lat} input

Study Participant Groups and Preparatory Material

- **21 participants** in total flew Blue Sim and Red Sim. They were divided into three groups:
  - **Group A:** Certified Flight Instructors (CFIs)
    - 5 participants
  - **Group B:** Individuals with pilot licenses, or undergoing pilot training at any level (but without CFI certificates)
    - 9 participants
  - **Group C:** Individuals holding driver licenses but not pilot licenses and without any pilot training
    - 7 participants
- For participants with flight experience, this data was captured through a pilot experience summary form
- All participants with flying experience came from fixed-wing general aviation backgrounds.
  - No rotorcraft experience
  - No military or airline flying experience (yet)

Table 3 Group A participant flight experience (* indicates undergoing training)

Identifier	Certificates & Ratings	PIC hours	Aircraft
A4	PPL, IR, CSEL, CMEL, CFI, CFII*	615	C172, AA5B, P28A, C152
A5	PPL, IR, CSEL, CMEL, CFI, CFII	477	C172
A6	PPL, IR, CSEL, CMEL, CFI, CFII*	337	C172, PA44
A7	PPL, IR, CSEL, CMEL, CFI, CFII*	755	C172, BDOG, P28A, PA44 DA40, RV7, C150, PA23
A8	PPL, IR, CSEL, CMEL, CFI, CFII*	269	C172, P28A

Table 4 Group B participant flight experience (* indicates undergoing training)

Identifier	Certificates & Ratings	PIC hours	Aircraft
B1	PPL, IR, CMEL*, RPC	283	C172, C152, P28A, PA44
B3	SPC, PPL*	3	C172
B4	PPL, IR, CMEL*	214	C172
B5	PPL, IR, CMEL*	240	C172
B6	PPL, IR, CMEL*, RPC	192	C172, PA44
B7	PPL, IR, CMEL*, RPC	138	C172, C150
B8	SPC, PPL*	9	C172
B9	PPL, IR, CSEL, CMEL, RPC	1209	C172, PA46, SR22, 7GCBC BE58, BE76, P28A, C240
B10	PPL, IR, CSEL*, CMEL*	223	C172, C182, DA40, P28A

Study Participant Preparatory Material

- Prior to their on-site visits, participants were given access to instructional videos explaining how to fly Blue Sim and Red Sim
  - These were narrated in *general terms*, avoiding excessive technical jargon
  - Maneuvering in vertical flight mode
  - Transitioning to forward flight mode
  - Maneuvering in forward flight mode
  - Transitioning to vertical flight mode

Blue Sim instructional video
https://www.youtube.com/watch?v=D-M-Zs26Xfs

Red Sim instructional video
https://www.youtube.com/watch?v=HHlrVYNM1yg

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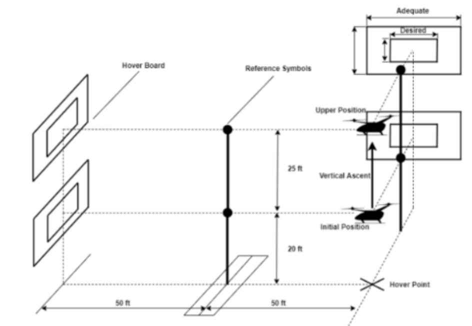
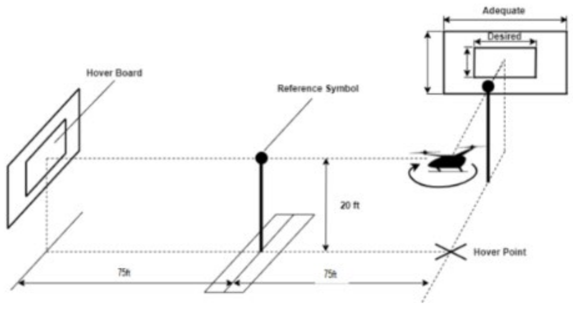
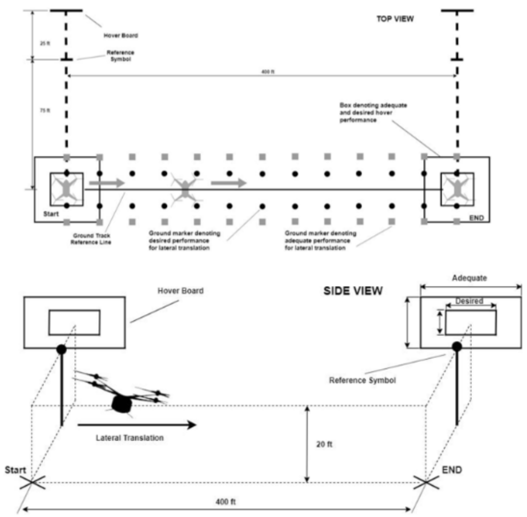
Simulation Tasks – Handling Qualities Task Elements (HQTEs)



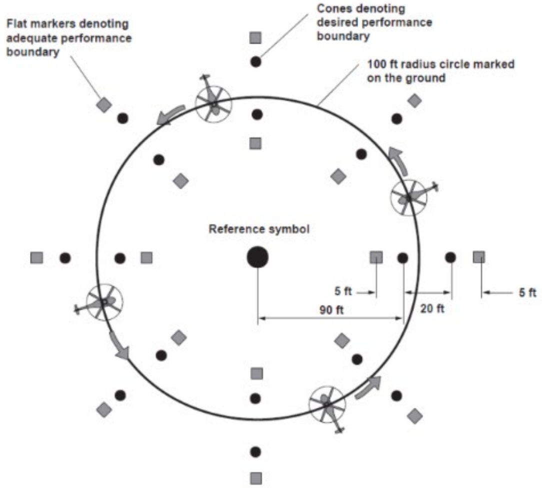
Vertical Reposition and Hold



Hovering Turn and Hold



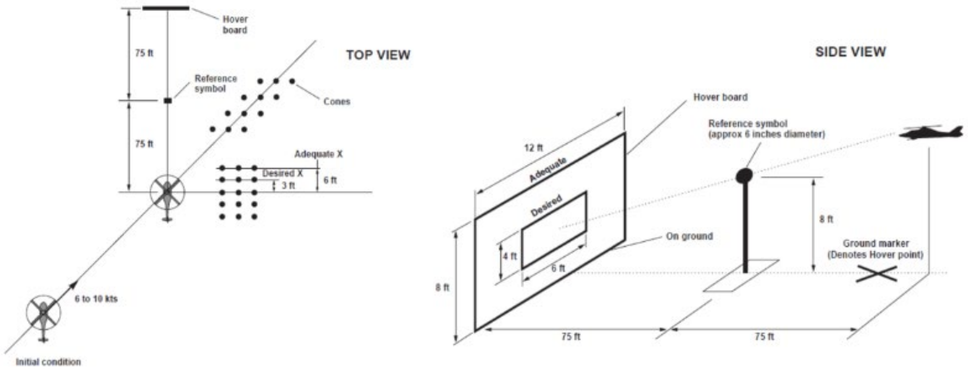
Lateral Reposition and Hold



Pirouette

Table 5 Activity schedule for Blue Sim and Red Sim simulation sessions

Item	Time allocation (min)	Cumulative time (min)
Data collection & ID assignment	5	5
Eye-point calibration	5	10
"Free flight" for VFM	5	15
"Free flight" for FFM	5	20
Vertical reposition & hold	15	35
Hovering turn & hold	15	50
(Mini-break)	5	55
Lateral reposition & hold	20	75
Pirouette	20	95
Precision hover	20	115
(Mini-break)	5	120
Transition to forward flight	20	140
UAM mission & heliport approach	20	160
(Buffer time)	20	180



Precision Hover

Klyde, D., Sizoo, D., Feary, M., Webber, D., and Schaller, R., "Handling Qualities Task Element Draft Version 1.0," submitted with cover letter to members of the eVTOL Flight Test Council and industry stakeholders, 16 September, 2021.

+ a simulated UAM "mission"

Task Descriptions Available to Participants

- Prior to each task, and while seated in the simulators, participants heard an audio recording describing each maneuvering task. It explained (in general terms) what to do for each task
- Link to YouTube video: https://www.youtube.com/watch?v=5_TaAk_jju0

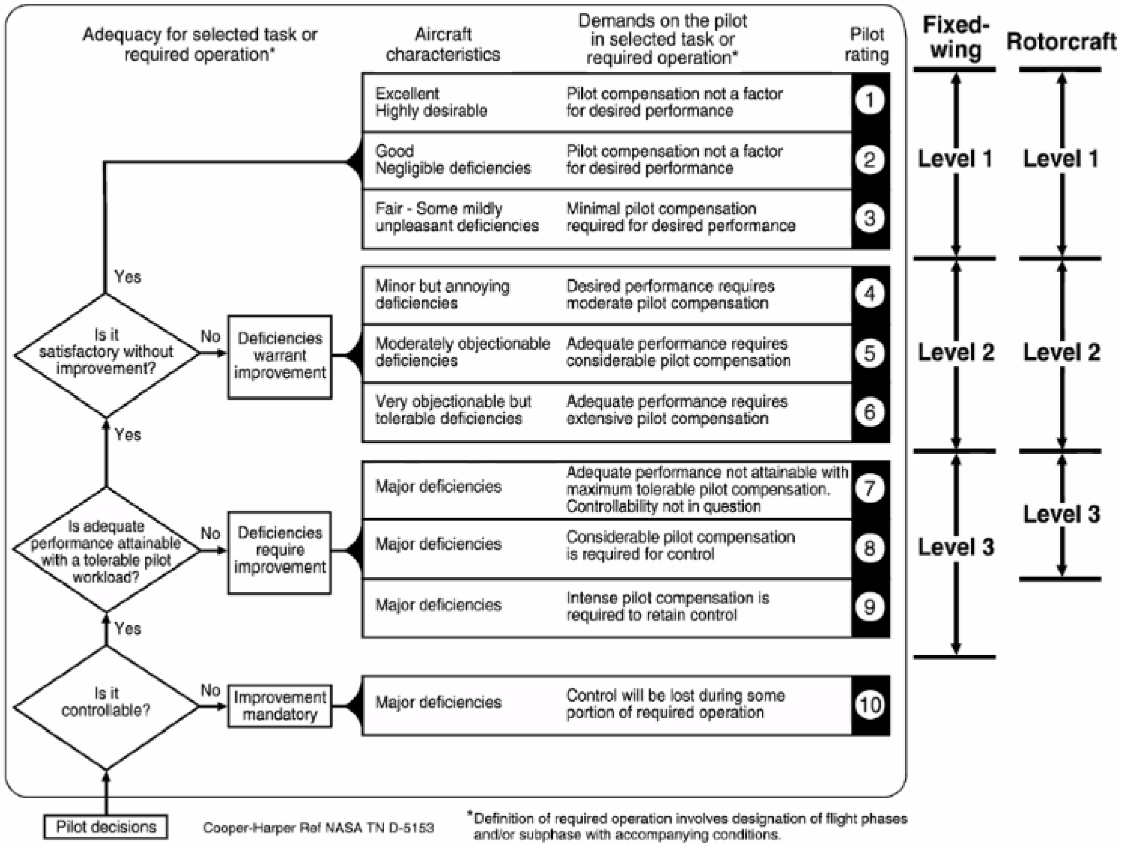
Derived Cooper-Harper Handling Qualities Ratings

- Q1. Did you find the aircraft to be controllable? Answer YES or NO below.
  • Yes
  • No (Earns CHR = 10)
  If you answered "YES" to Q1, please answer the following:

- Q2. Were you able to perform the task adequately with tolerable pilot workload (defined as how hard you had to work to perform the task)?
  • Yes
  • No. I had to work intensely in order to maintain control of the aircraft. (CHR = 9)
  • No. I had to work considerably hard in order to maintain control of the aircraft. (CHR = 8)
  • No. The aircraft was controllable, but my workload was still too high to perform the task adequately. (CHR = 7)
  If you answered "YES" to Q2, please answer the following:

- Q3. In your opinion, are the aircraft characteristics that you experienced satisfactory, without any further improvement?
  • Yes
  • No. There were very objectionable but tolerable deficiencies. Extensive control corrections were required to perform the task adequately. (CHR = 6)
  • No. There were moderately objectionable deficiencies. Considerable control corrections were required to perform the task adequately. (CHR = 5)
  • No. There were some minor but annoying deficiencies. Moderate control corrections were required to perform the task adequately. (CHR = 4)
  If you answered "YES" to Q3, please answer the following:

- Q4. How would you rate the aircraft flight characteristics that you experienced on this task?
  • Fair. The task could be performed adequately with minimal control corrections. (CHR = 3)
  • Good (CHR = 2)
  • Excellent (CHR = 1)



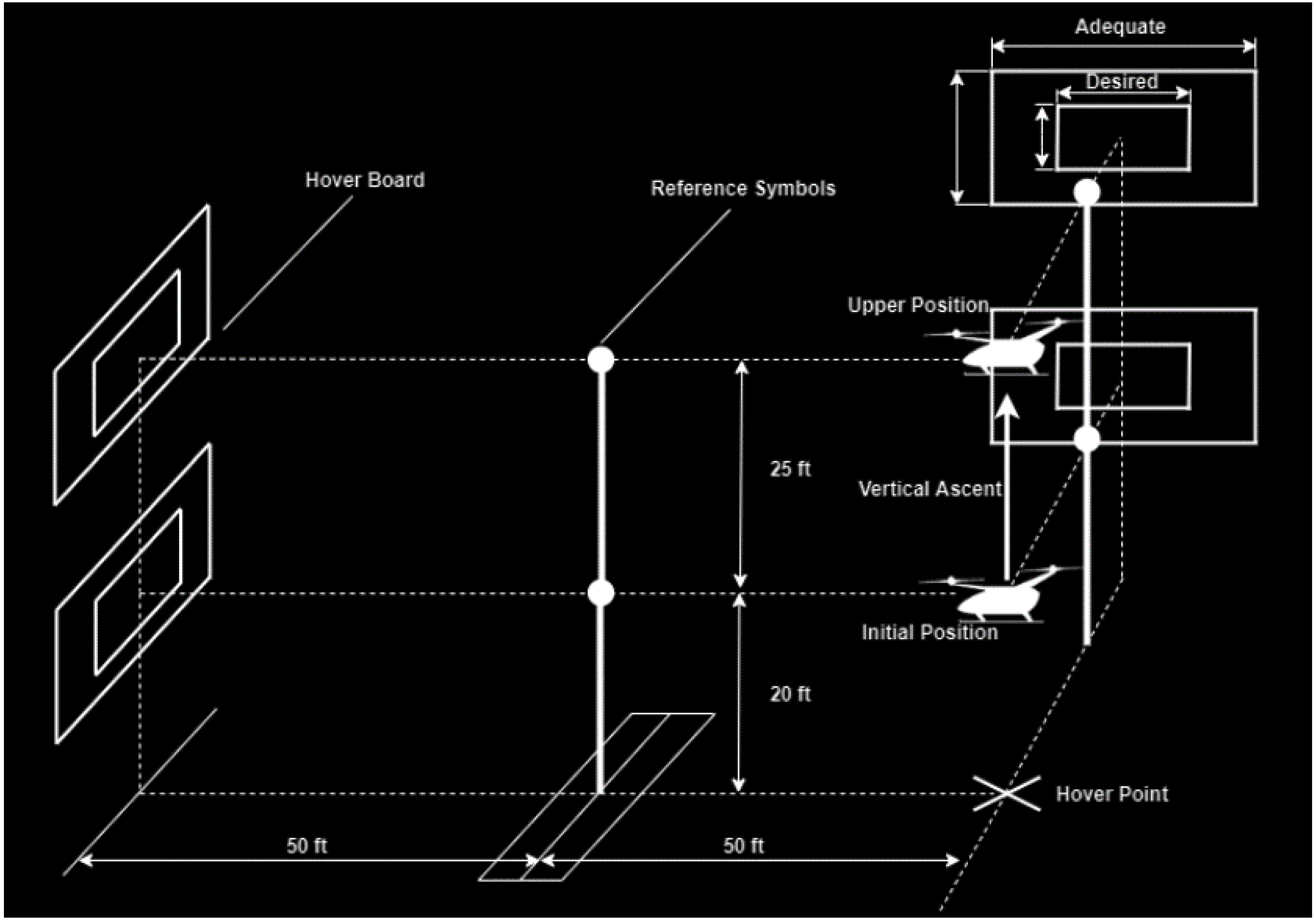
Level 1: Satisfactory without improvement ("desired performance", "satisfactory")

Level 2: Deficiencies warrant improvement ("adequate performance", "acceptable")

In addition, participants could log qualitative/textual feedback about each HQTE. The verbatim comments of all participants are available from →

Chakraborty, I., et al., *"Piloted Simulation Based Assessment of Simplified Vehicle Operations for Urban Air Mobility,"* AIAA SCITECH 2023 Forum, National Harbor, MD & online, 23-27 January, 2023, AIAA-2023-0400

Vertical Reposition and Hold HQTE

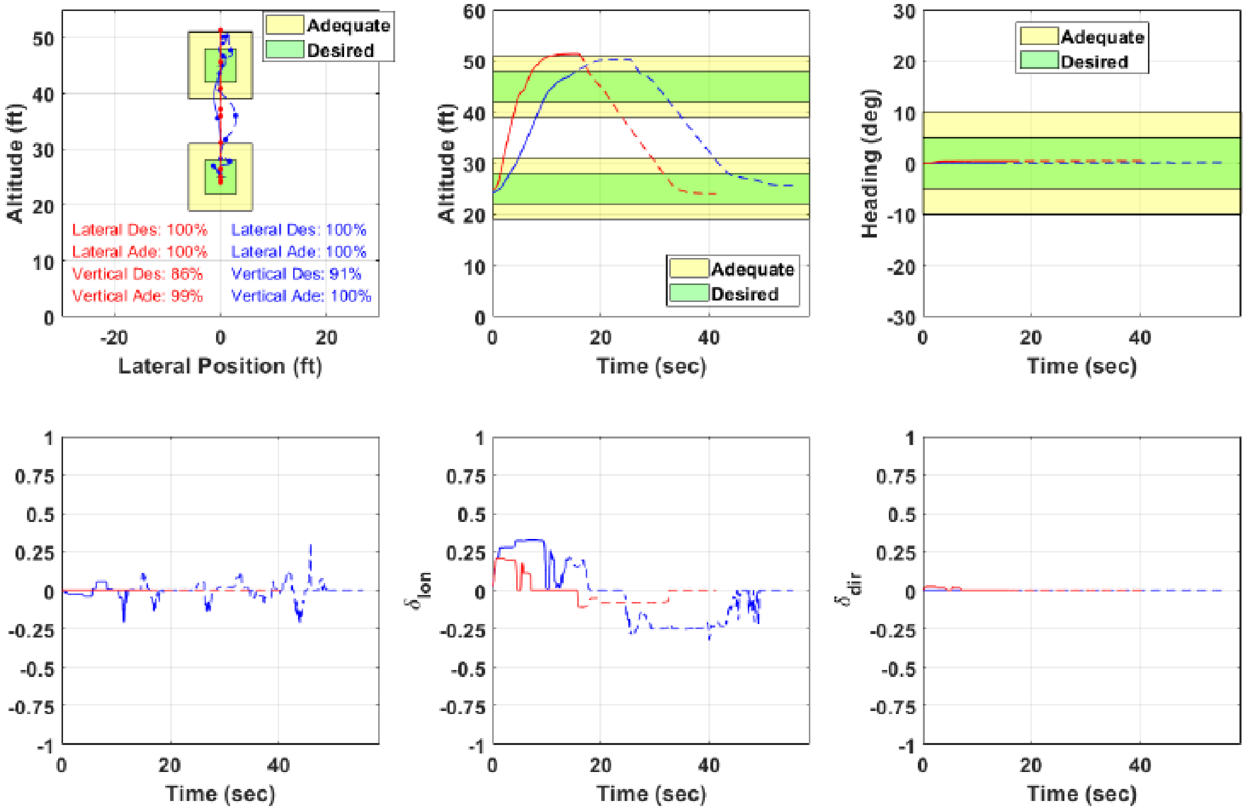


"The vertical reposition and hold task. In front of you is a hover board. If you look to your right, you will see another hover board. When the black ball between you and each hover board is aligned with the center of the "X" marked on the yellow square on the hover board, you are perfectly aligned with the board. For practical purposes, your target is to see the black balls within the inner yellow squares. Take a moment to note this sight picture, both ahead of you and to your right. Your objective is to climb vertically and come to a hover aligned in just this manner with the two hover boards that are 25 feet above your current altitude, one in front, and one to the right. Stabilize the aircraft in a hover up there for approximately 5 seconds. Then, descend vertically back to your current altitude and align yourself with the two lower hover boards. Remember, refer to both the boards in front and the ones to your right side when checking your alignment. To hear these instructions again, use the PREV and NEXT buttons to cycle away from and then back to this task description. Begin when ready, and when you are finished, call out "COMPLETE" on the intercom."

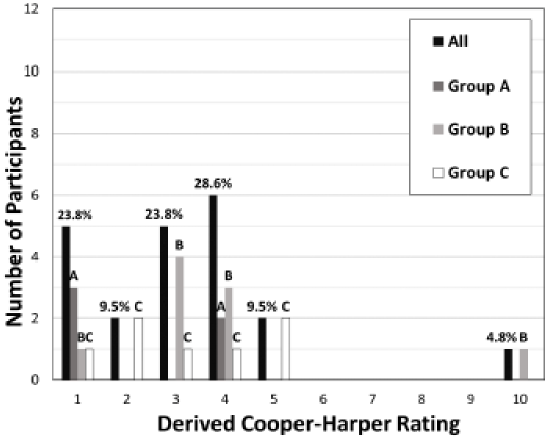
Vertical Reposition and Hold HQTE

- Climb rate commands in VFM are generated by
  - Fore-aft motion of the Right-Hand Inceptor in **Blue Sim**
  - Up-down motion of the Left-Hand Inceptor in **Red Sim**
- Several participants reported undesirable coupling between lateral input and vertical axis input in **Blue Sim**
- No participants reported undesirable coupling between vertical and directional inputs in **Red Sim**

Vertical Reposition and Hold, Participant A4, Red Sim vs. Blue Sim

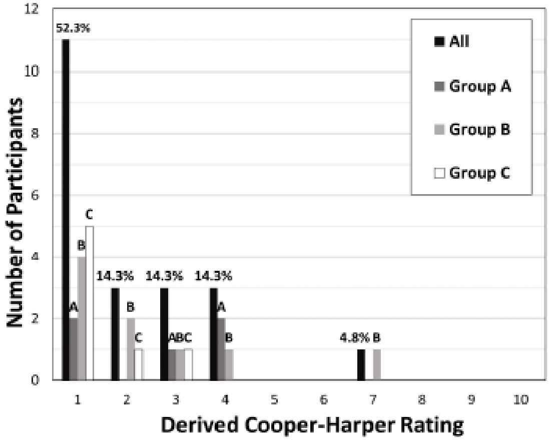


Vertical Reposition and Hold CHR, Blue Sim



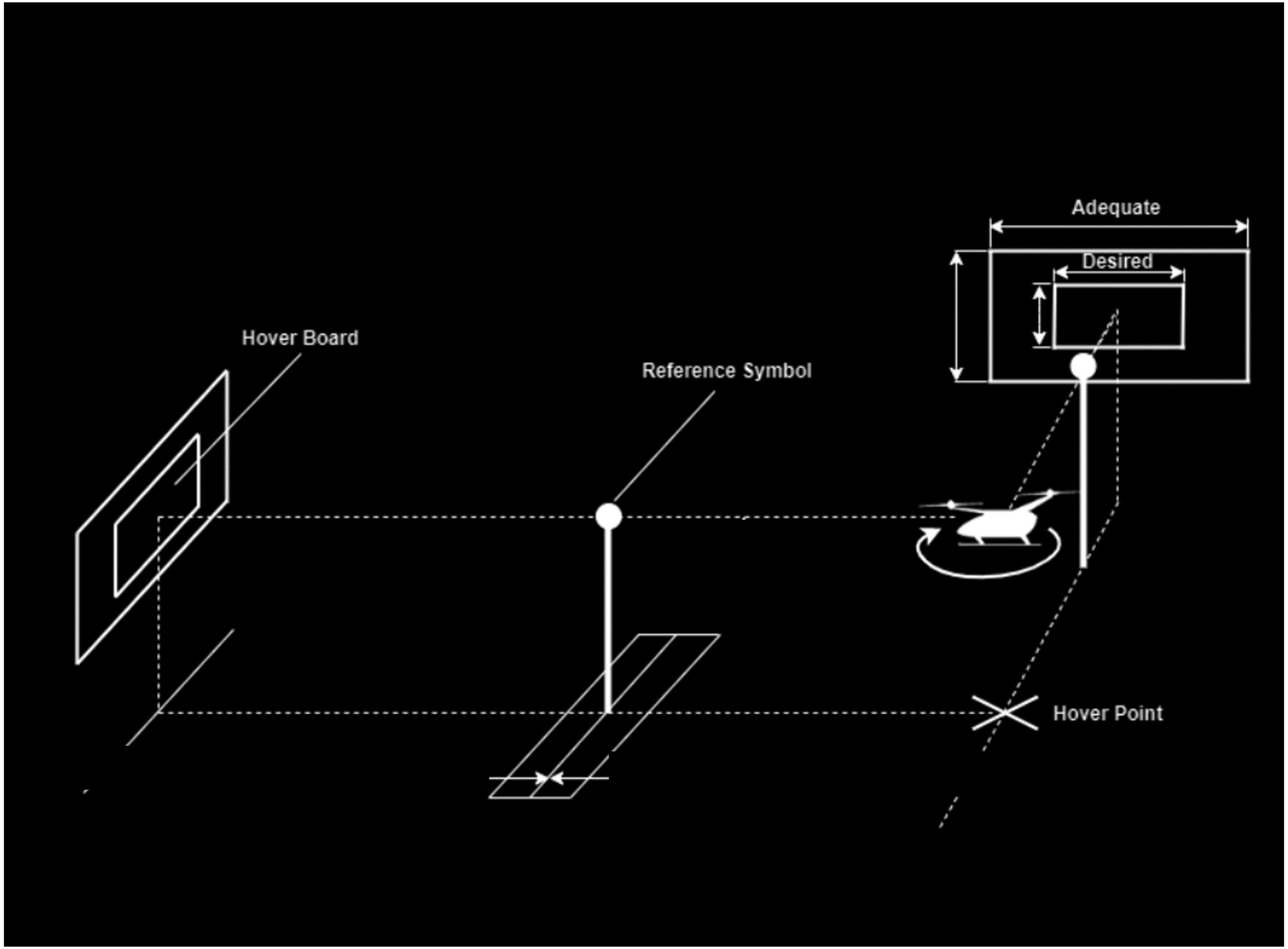
L1: 57.1%, **L2:** 38.1%, **L3:** 4.8%

Vertical Reposition and Hold CHR, Red Sim



L1: 80.9%, **L2:** 14.3%, **L3:** 4.8%

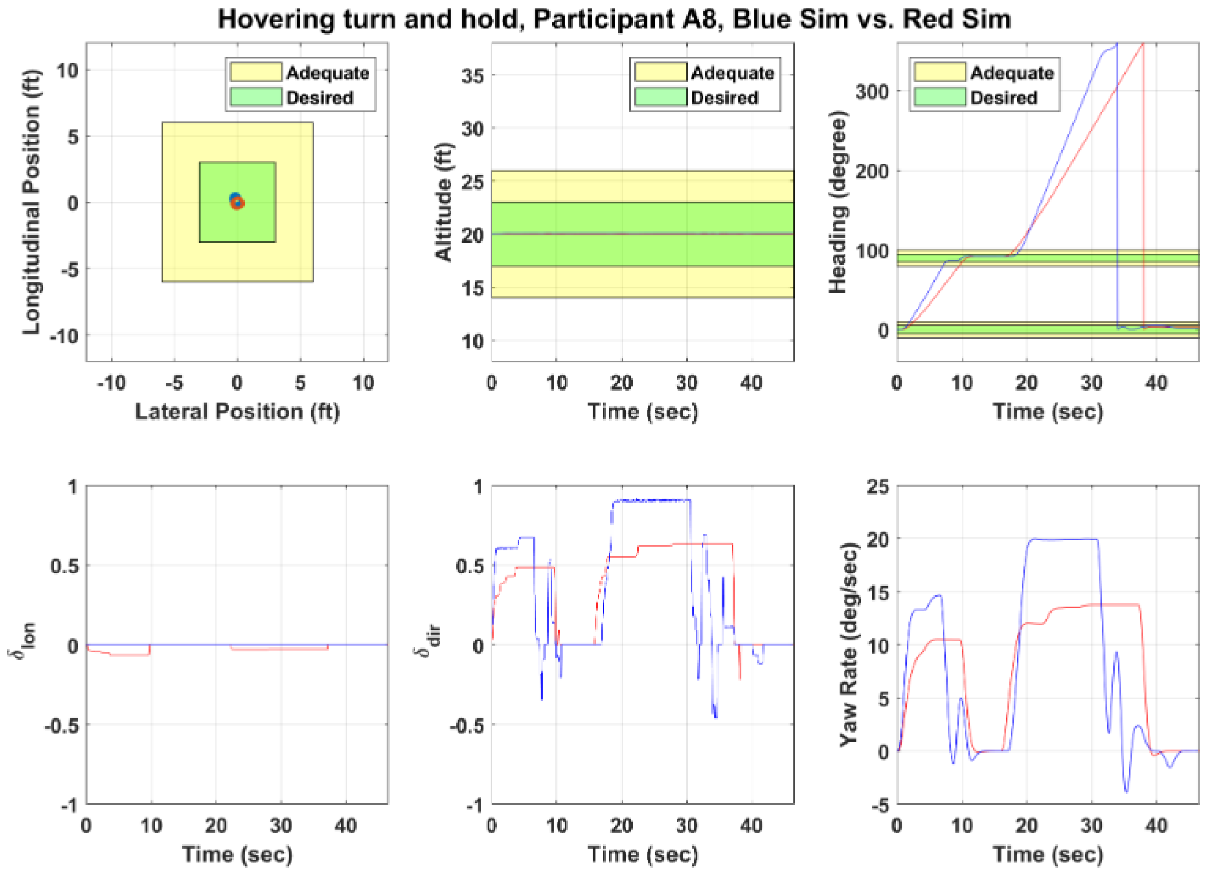
Hovering Turn and Hold HQTE

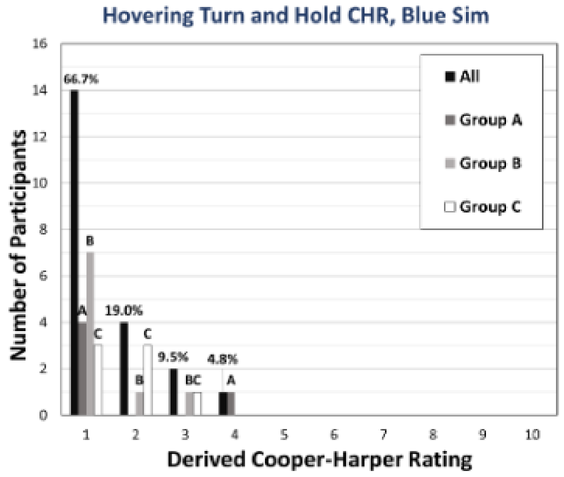


"The hovering turn and hold task. There is a hover board in front of you. Check your left and right sides. On one side, you will see another hover board. When the black ball between you and each hover board is aligned with the center of the "X" marked on the yellow square on the hover board, you are perfectly aligned with the board. For practical purposes, your target is to see the black balls within the inner yellow squares. Take a moment to note this sight picture, both ahead of you and to the side. Your objective is to turn the aircraft 90 degrees to face the hover board which is currently off to your side. Once you have done this, verify your alignment by referring to both the hover boards, and correct if necessary. Stabilize in a hover like this for approximately 5 seconds. Then, turn in the same direction as before a further 270 degrees to bring the nose to point towards the first hover board, thereby completing a full turn. Once again, check your alignment and stabilize in a hover for 5 seconds. To hear these instructions again, use the PREV and NEXT buttons to cycle away from and then back to this task description. Begin when ready, and when you are finished, call out "COMPLETE" on the intercom."

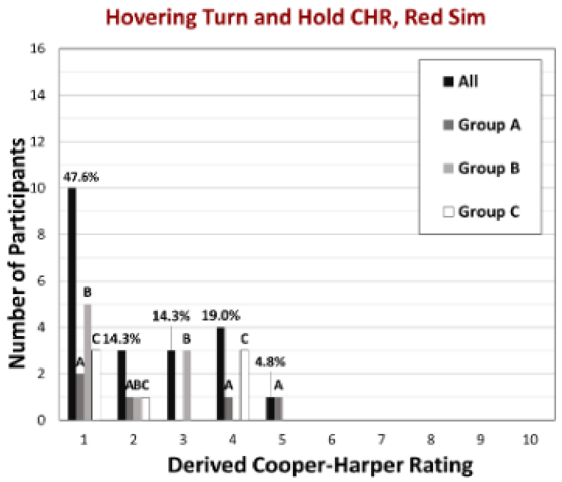
Hovering Turn and Hold HQTE

- Yaw rate commands in VFM are generated by
  - Left-right twist of the Right-Hand Inceptor in **Blue Sim**
  - Left-right motion of the Left-Hand Inceptor in **Red Sim**
- Several participants reported inadvertent cross-coupling of intended yaw rate inputs (LHI left/right) with unintended vertical axis inputs (LHI up/down) in **Red Sim**
- This type of cross-coupling was not reported in **Blue Sim**, though several participants commented on the ergonomics and symmetry of the "twist-top" RHI



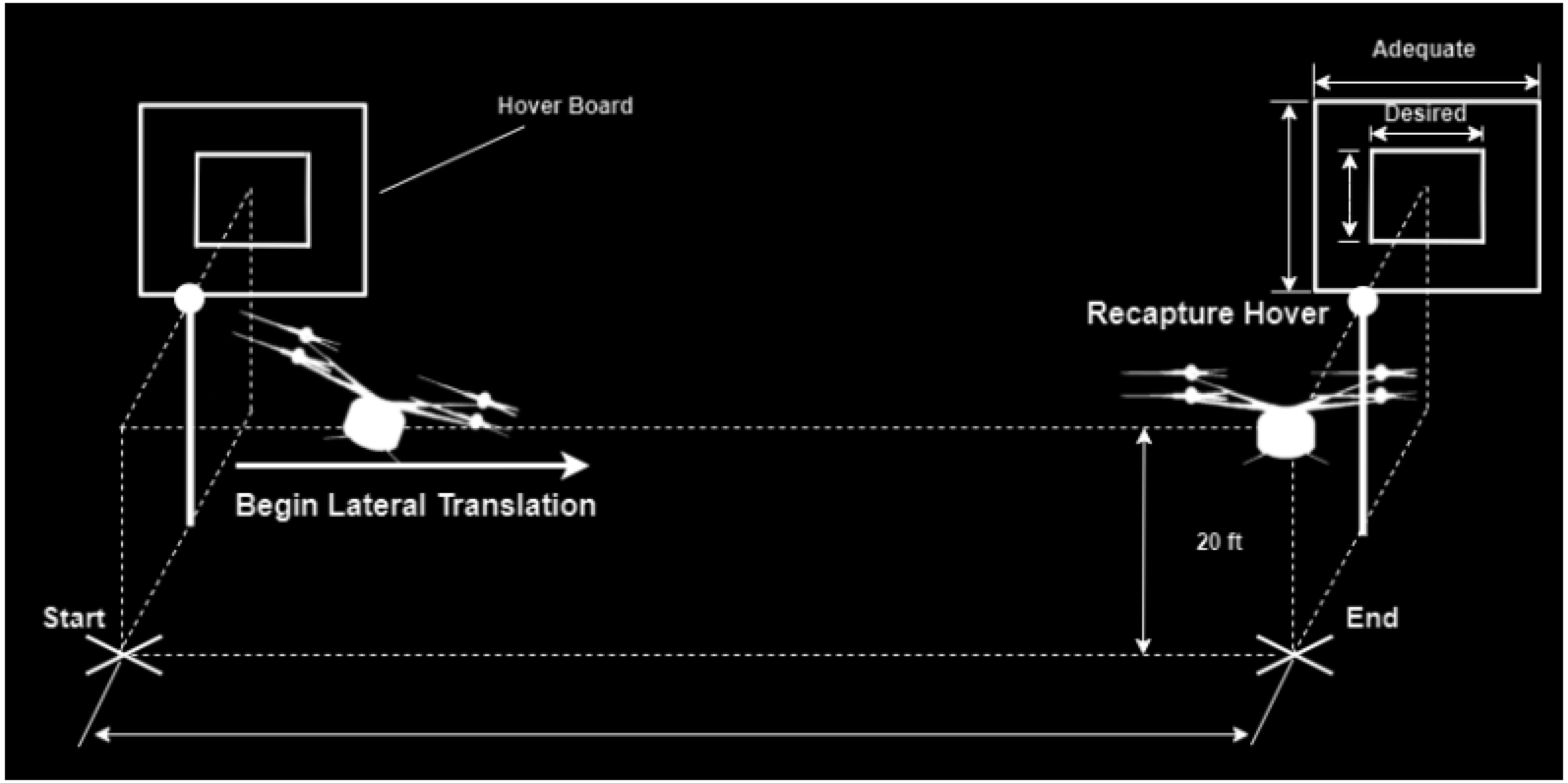


L1: 95.2%, **L2:** 4.8%



L1: 76.2%, **L2:** 23.8%

Lateral Reposition and Hold HQTE



"The lateral reposition and hold task. There is a hover board in front of you. When the black ball between you and the hover board is aligned with the center of the "X" marked on the yellow square on the hover board, you are perfectly aligned with the board. For practical purposes, your target is to see the black ball within the inner yellow square. Take a moment to note this sight picture. Now, look to your right side. There is a 400-foot long path. At the end of it is another hover board, just like the one in front of you. Your objective is to move the aircraft laterally, or sideways, down this 400-foot long path, while remaining above the solid white centerline. Look for the red tape markings on the sides of the cockpit to help you with this alignment. As you move sideways, maintain a lateral velocity between 10 and 15 knots and maintain your current altitude. As you near the end of the path, slow down, and come to a hover aligned with the hover board at the end of the path. Stabilize in hover for approximately 5 seconds. Then, repeat exactly the same maneuver in the opposite direction. Move sideways to the left and head back towards the starting hover board. Come to a stabilized hover aligned with the starting hover board for approximately 5 seconds. After this, call out "COMPLETE" on the intercom. To hear these instructions again, use the PREV and NEXT buttons to cycle away from and then back to this task description. Begin when ready."

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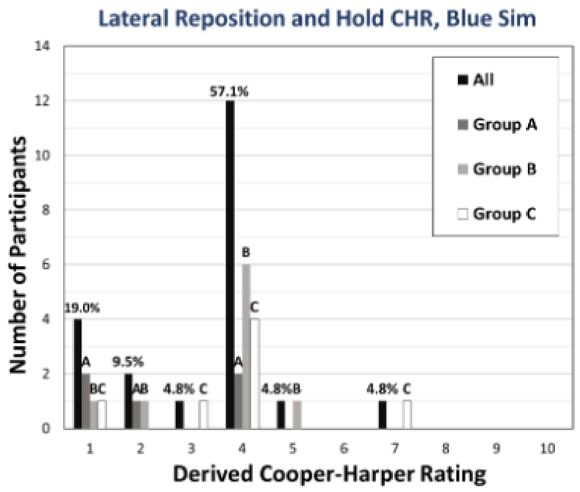
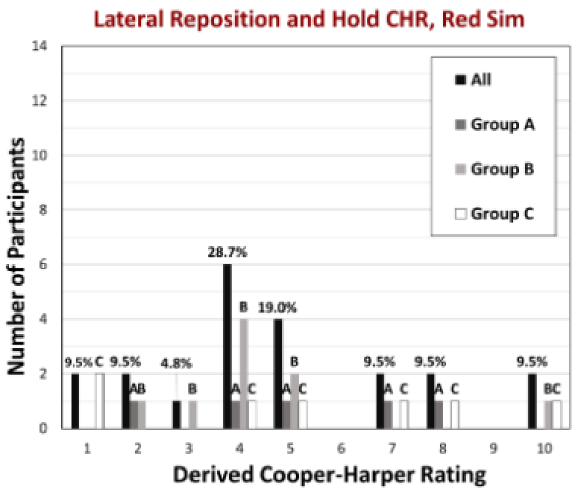
Lateral Reposition and Hold HQTE

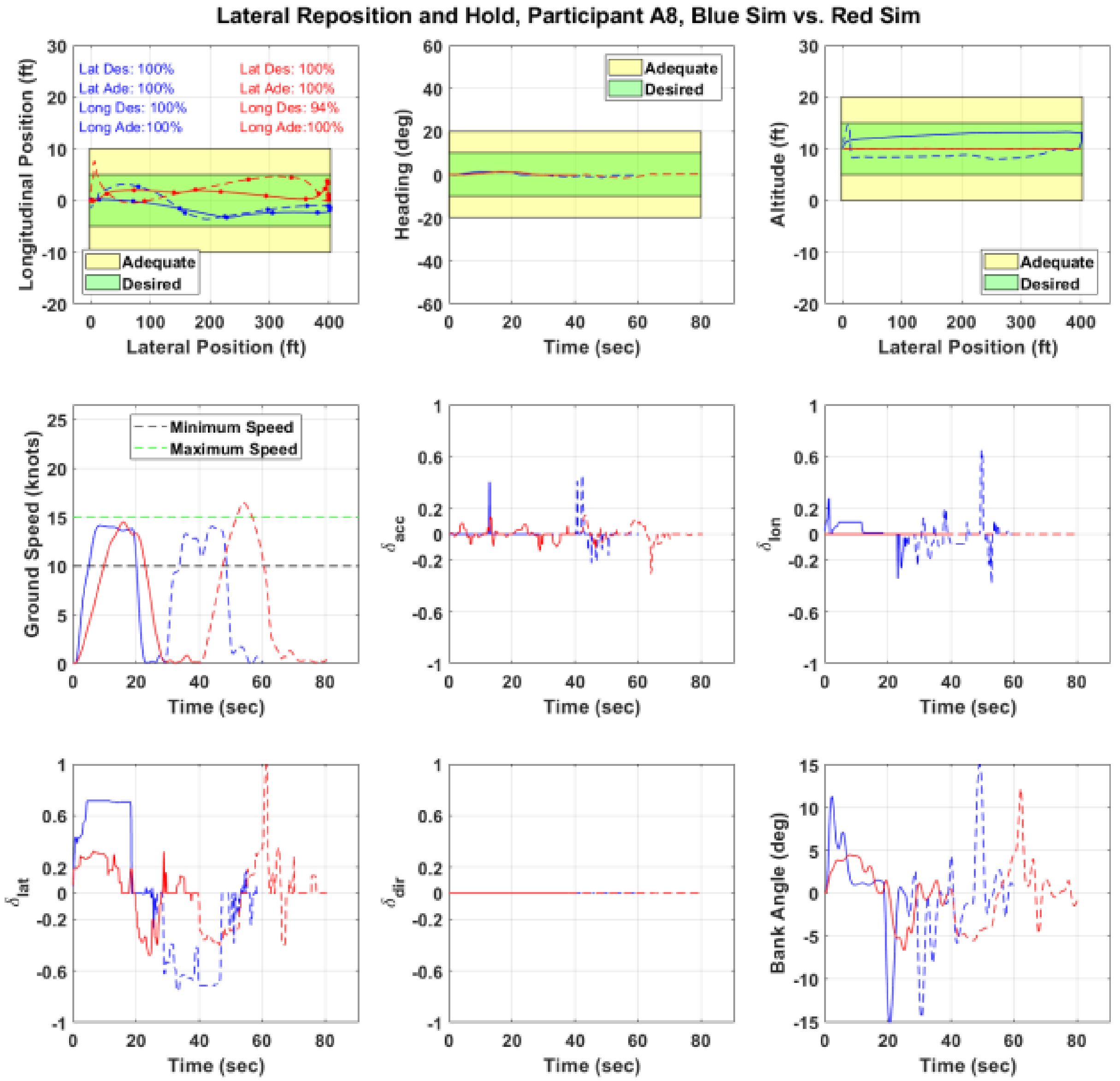
- The left-right motion of the Right-Hand Inceptor
  - Commands **lateral velocity** in **Blue Sim**
  - Commands **bank angle** in **Red Sim**
- Participants noted greater difficulty in bringing the aircraft to a stop in **Red Sim**
- Some participants reported undesirable coupling between lateral input and vertical axis input (RHI fore/aft) in **Blue Sim**
- Some participants reported undesirable coupling between lateral input and acceleration input (RHI fore/aft) in **Red Sim**



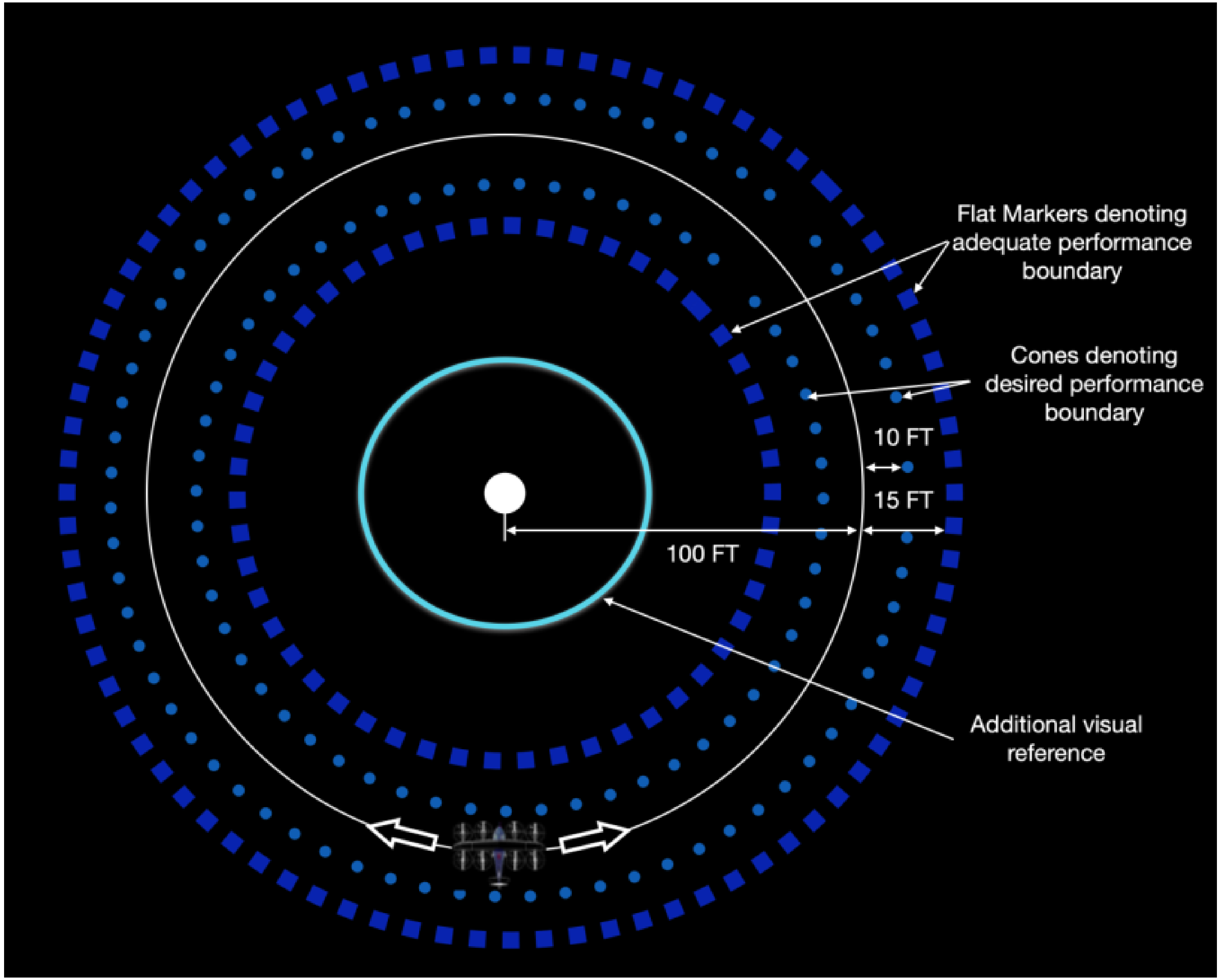
L1: 33.3%, **L2:** 61.9%, **L3:** 4.8%



L1: 28.5%, **L2:** 47.7%, **L3:** 28.5%



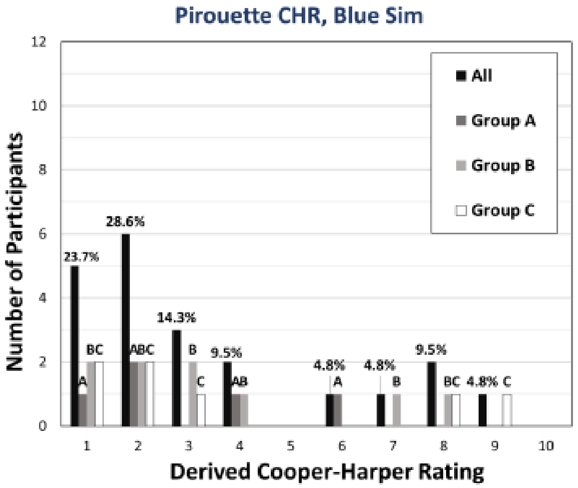
Pirouette HQTE



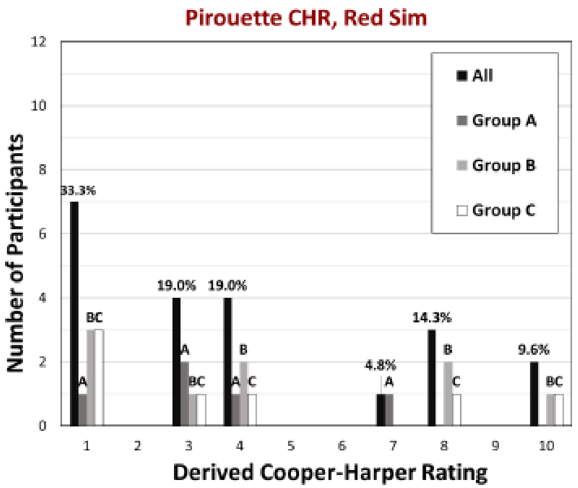
"The pirouette task. You are hovering on the circumference of a circular path, marked by the dashed white line that you can see to either side of you. In front of you, there is a white pole with a black ball on top of it, located at the center of the circle. Your objective is to fly the aircraft laterally, or sideways, over the circumference of the circle while keeping the nose pointed towards the pole at all times and maintaining your current altitude. Therefore, while flying this maneuver, you will have to alternate your vision between the front and the side. Look primarily out the side, using the red tape markings on the sides of the cockpit to help you align over the dashed white circumference line. You should also periodically look forward and verify if the nose is pointed at the pole, correcting if necessary, and also verify your altitude on the primary flight display. As indicated by the speed sign in front of you, you will begin the maneuver by flying sideways at 4 knots. The investigator will inform you whether to fly to the left or to the right. There are boards every 30 degrees to indicate your progress. When you complete a half-circle and reach the 180-degree marker, you will see a speed sign asking you to speed up to 6 knots. Fly the remaining half-a-circle at 6 knots. When you have completed the circle, return to a hover aligned with the 0-degree marker, and call out "COMPLETE" on the intercom. To hear these instructions again, use the PREV and NEXT buttons to cycle away from and then back to this task description. Begin when ready."

Pirouette HQTE

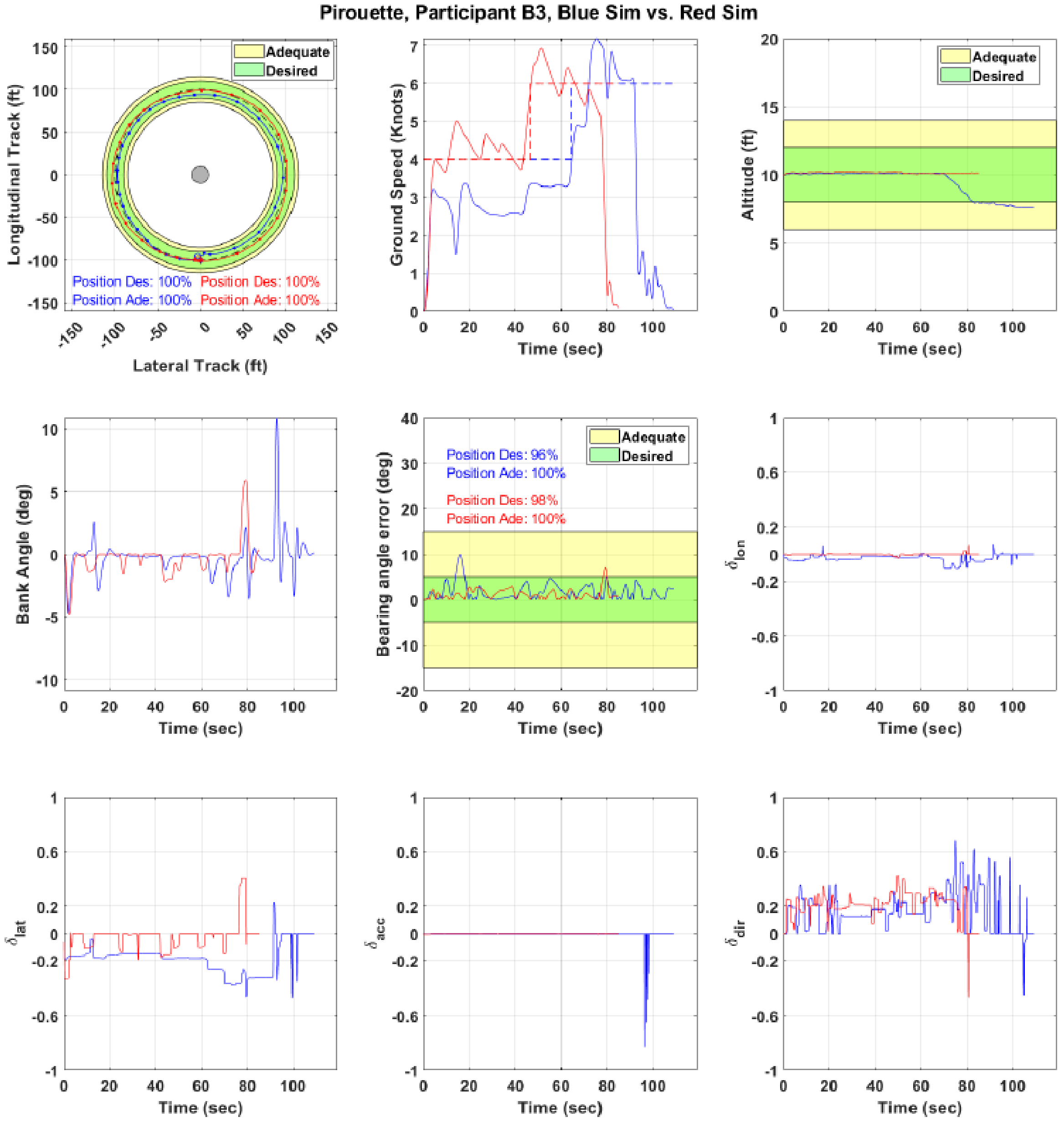
- **Blue Sim:** Simultaneous left-right input of the Right-Hand Inceptor + CCW/CW twist of the RHI "twist-top"
- **Red Sim:** Simultaneous left-right input of the RHI + right/left input of the LHI
- Some participants reported undesirable coupling between lateral input and vertical axis input in Blue Sim
- Some participants reported undesirable coupling between directional and vertical inputs in Red Sim



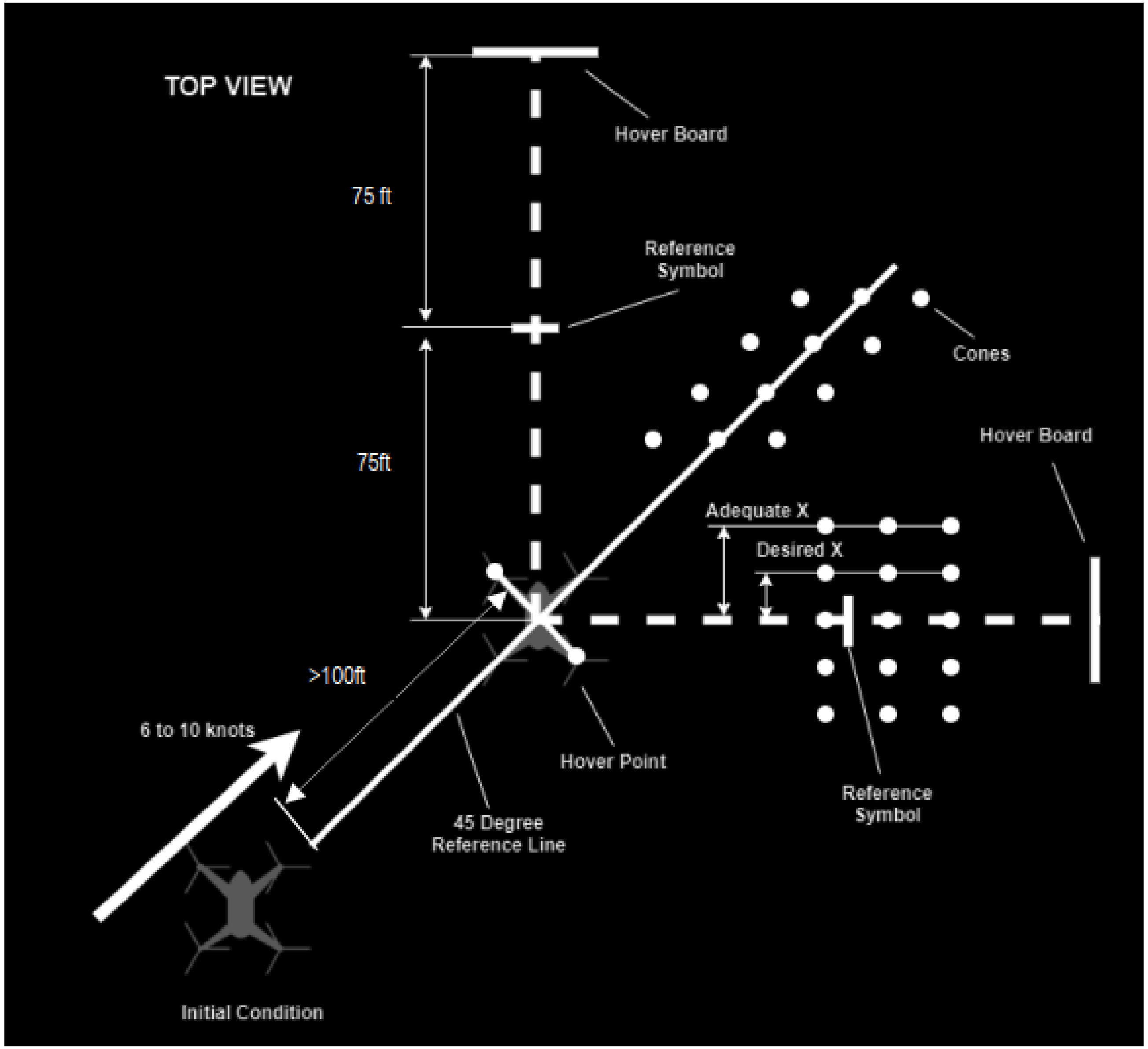
L1: 66.6%, **L2:** 14.3%, **L3:** 19.1%



L1: 52.3%, **L2:** 28.6%, **L3:** 19.1%



Precision Hover HQTE



"The precision hover task. Look 45 degrees to your right. You will see a solid white line on the ground heading away from you towards a red and yellow target box drawn on the ground. Your objective is to fly the aircraft diagonally, in a crab-like motion, over this white line, finishing in a stabilized hover over the target box drawn on the ground. Maintain a speed of between 6 to 10 knots, and maintain your current heading and altitude at all times. Remember, you will fly in a diagonal, crab-like motion. As you approach the target box, you will lose sight of it as it disappears under your aircraft. Therefore, use the two hover boards located on two sides of the target box to align yourself. One hover board will appear in front of you, and the other to your right. When the black ball between you and each hover board is aligned with the center of the "X" marked on the yellow square on the hover board, you are perfectly aligned with the board. For practical purposes, your target is to see the black balls within the inner yellow squares. When you have reached the target box, align yourself using the hover boards and maintain a stabilized hover for approximately five seconds. Then, call out "COMPLETE" on the intercom. To hear these instructions again, use the PREV and NEXT buttons to cycle away from and then back to this task description. Begin when ready."

Precision Hover HQTE

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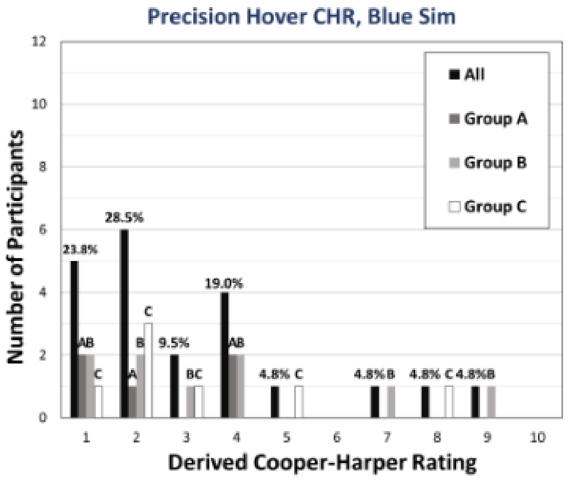
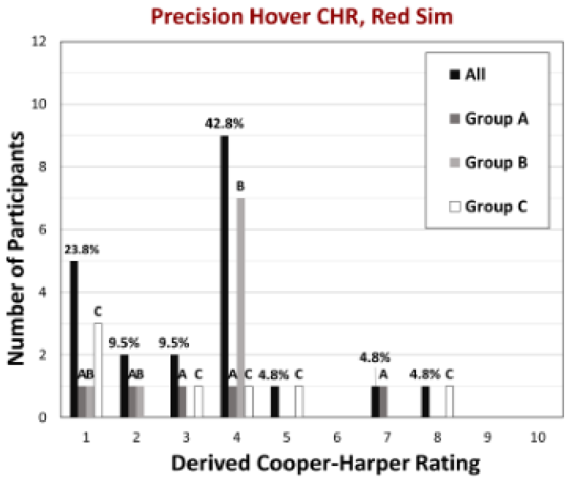
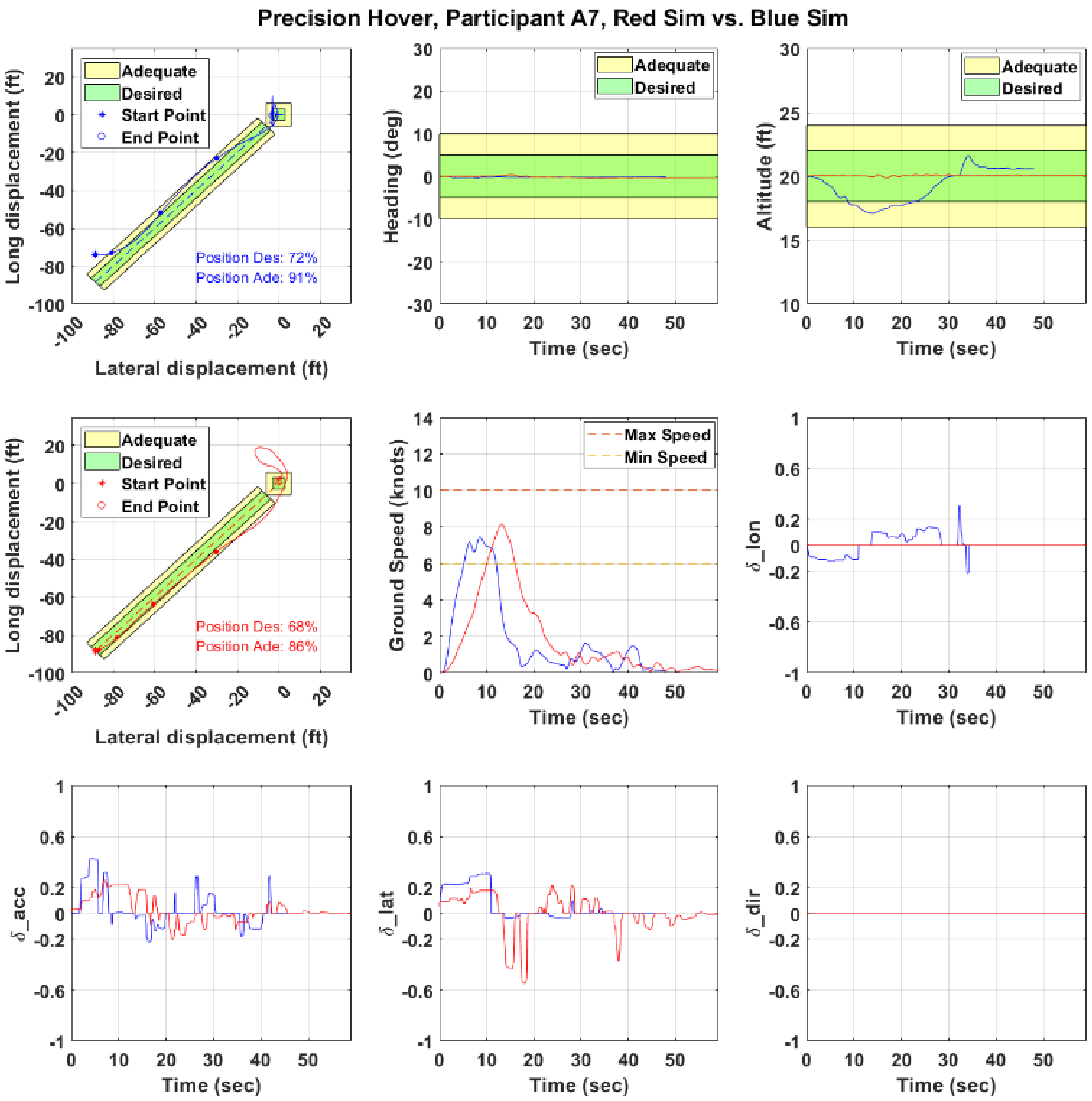
- **Blue Sim:** Forward movement: LHI fore-aft; lateral movement: RHI left-right
  - At least one participant reported undesirable coupling of a vertical axis input (RHI fore-aft)
- **Red Sim:** Forward movement: RHI fore-aft; lateral movement: RHI left-right
  - Several participants noted increased workload to neutralize the lateral velocity
  - Some participants opined that having both fore-aft and lateral motions on the RHI helped for this HQTE



L1: 61.8%, **L2:** 23.8%, **L3:** 14.4%



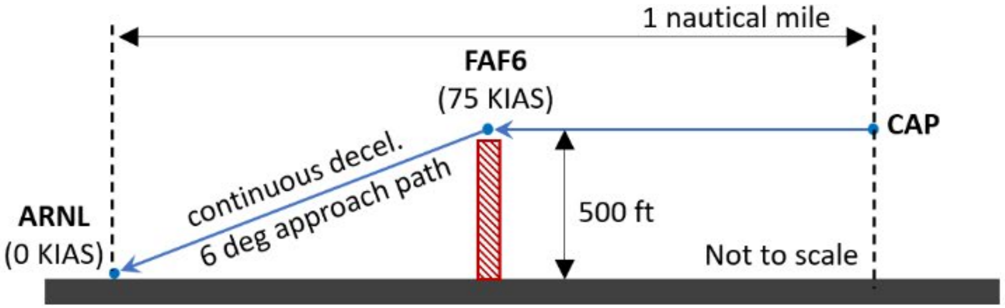
L1: 42.8%, **L2:** 47.6%, **L3:** 9.6%

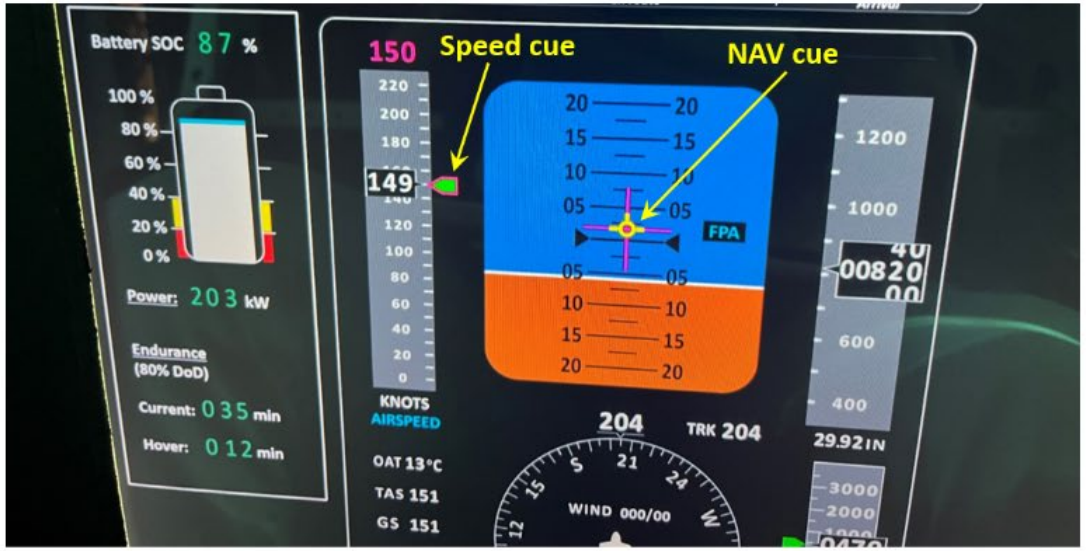


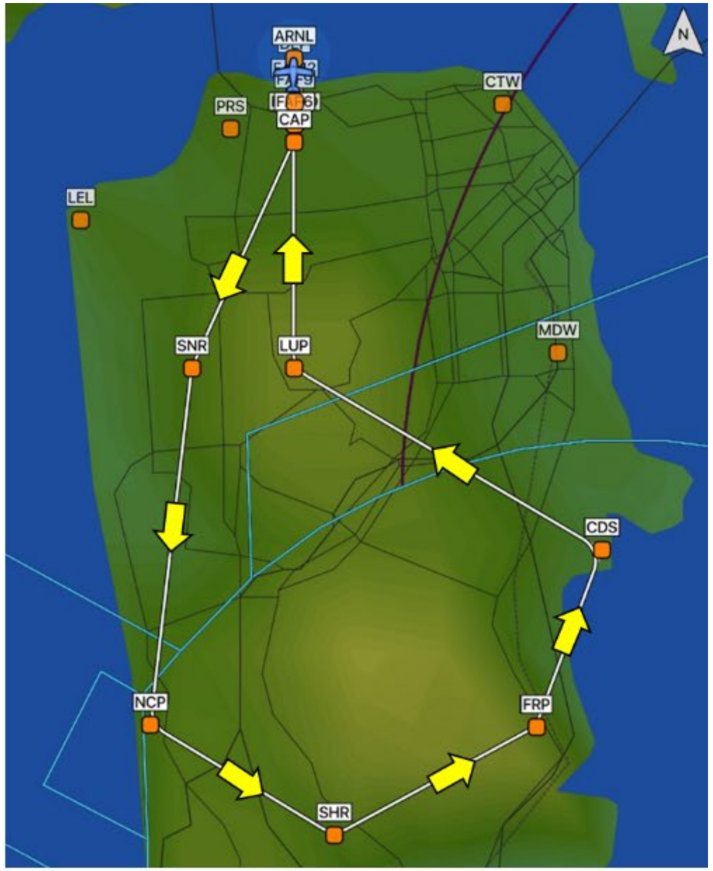
UAM "Mission" Simulation

- Participants were asked to fly a UAM "mission" from takeoff to landing.
  - Take off →
  - Transition while clearing an obstacle →
  - Follow enroute waypoints →
  - Transition to vertical flight →
  - Clear obstacle on approach path →
  - Land on pad

- Participants "hand flew" the mission while following Flight Director guidance and speed cues





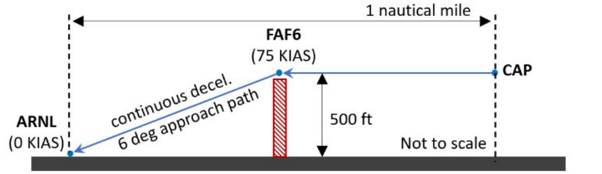


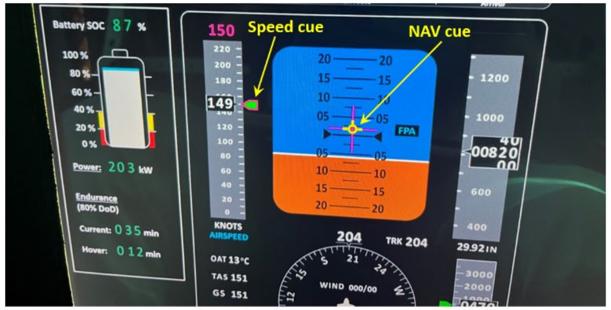
UAM mission flight-plan: ARNL → FAF6 → SNR → NCP → FRP → CDS → LUP → CAP → FAF6 → ARNL

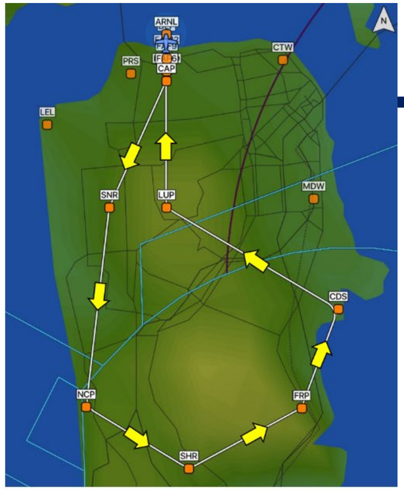
VFM -> FFM transition | Enroute navigation | FFM -> VFM transition | Final approach

UAM Mission Simulation

- One astute participant reported that the TECS algorithm switched several times between “speed priority” and “path priority” during transition.
  - Cause identified; will be rectified
- Several participants commented on pitch transients that occurred during transition.
  - These occur when the lift propulsors turn on or turn off.
- Some participants with fixed-wing backgrounds noted confusion regarding speed control via fore-aft movement of the RHi in Red Sim
- Several participants noted difficulty in simultaneously decelerating and descending
- Several participants noted that the flight director guidance cues were not precise enough to guide them to a landing.
  - Flight director gains need to be “tuned”

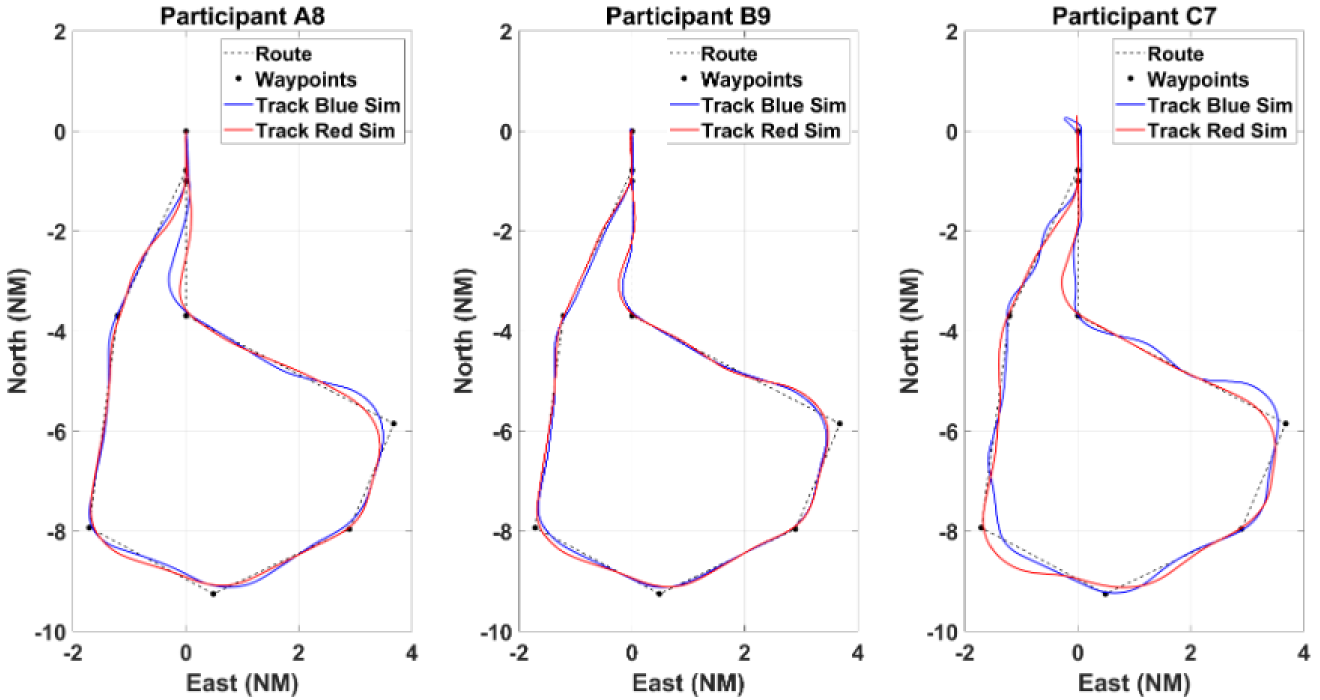






UAM mission flight-plan: ARNL → FAF6 → SNR → NCP → FRP → CDS → LUP → CAP → FAF6 → ARNL

VFM -> FFM transition | Enroute navigation | FFM -> VFM transition | Final approach



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Conclusions and Future Work

- Participants in all three categories (including non-pilots) were able to perform the tasks with relatively little instruction, training, or practice
- Some coupling between inceptor axes was noted from the logged simulator data and also corroborated by participant feedback – the coupling occurred for different HQTEs for the two different inceptor designs. This warrants further investigation
- Current study participants had only fixed wing aircraft experience (or none at all). Future studies will focus on recruiting participants with more diverse aviation backgrounds (rotorcraft, military, airline experience…) and experience levels
- The HQTEs that were assessed in this study corresponded to hovering/vertical flight mode. Additional HQTEs corresponding to forward flight will be evaluated in future work
- Simulations in the current work were performed in calm air conditions, in good visual environment, with a nominal vehicle state (no failure). Future work will feature simulations in windy/gusty/turbulence conditions, degraded visual environments, and with control effector or system failures that stress the pilot-vehicle system.