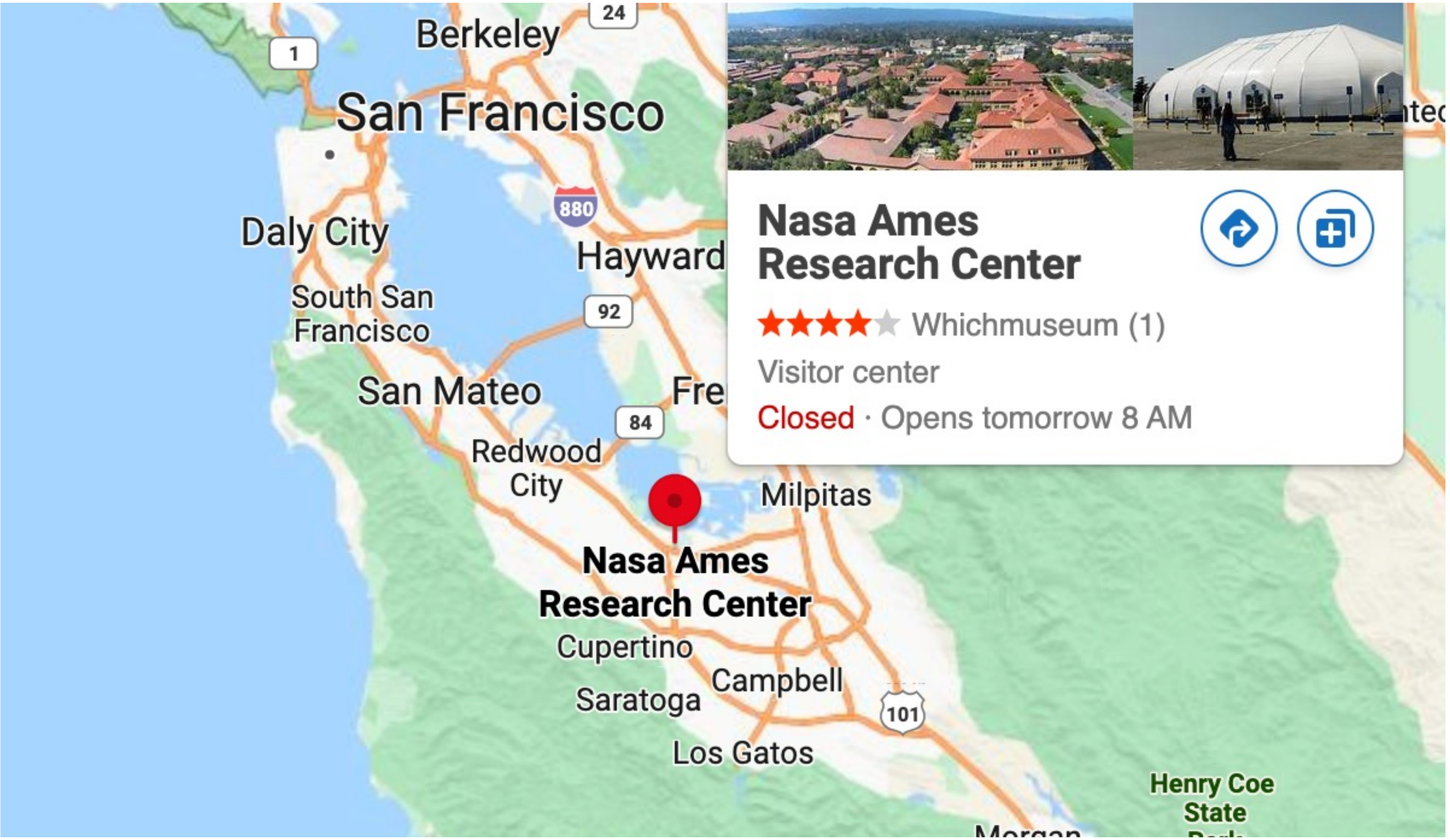
Advancing Electric Propulsion Aircraft Evaluation for Urban Air Mobility: Insights from NASA-Ames

- Loran Haworth, Michael S. Feary, John Kaneshige, and Thomas Lombaerts
- NASA Ames Research Center, Moffett Field, CA, 94035, USA
- SETP NW

Introduction: NASA Ames Research Center Location



Nasa Ames Research Center

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Visitor center

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Presentation Outline

Symposium and presentation purpose

Brief Introduction - NASA-Ames and selected VTOL History

Programmatic Background and eVTOL Flight Challenges.

History and Rationale for applying Aeronautical Design Standard -33 (ADS-33) Mission Task Elements (MTEs) for eVTOL

Insights and lessons learned gained while applying ADS-33 during simulation

Electric Vertical Takeoff and Landing (eVTOL) simulation at NASA-Ames Research Center (AEP-1) applying Mission Task Elements (MTEs)/Flight Test Task (FTT)

Questions and comments

Symposium Purposes

The Society of Experimental Test Pilots
13th Annual Northwest Section
Symposium
Seattle, Washington
19 April 2024

The purpose of "this Symposium is to share the knowledge gained in the course of planning, execution and documentation of flight test activities" in the spirit of sharing lessons learned.

Our purpose in this presentation is to:

- <u>Share knowledge</u> gained during planning the application and adaption of Aeronautical Design Standard -33 (ADS-33) for eVTOL handling qualities and the
- <u>execution and documentation</u> of NASA's Automation Enabled Pilot Study 1 (AEP-1) AEP-1 in NASA's large motion Vertical Motion Simulator (VMS)

Advanced Air Mobility & Revolutionary Vertical Lift Technology Project

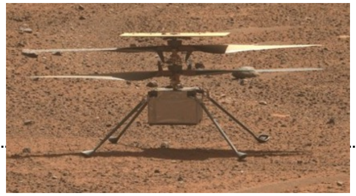
- **Advanced Air Mobility**

Airspace is no longer only for large aircraft high above—it is overhead in urban environments and will soon hover just above our doorsteps. This will require even more intense management. As these new forms of flight become more common, including the air taxis and air cargo delivery drones that Advanced Air Mobility envisions, NASA leads the collaborative effort between government, industry, and academic partners to ensure they integrate the airspace safely and efficiently. Software development and simulation facilities at Ames are integral parts of this research.

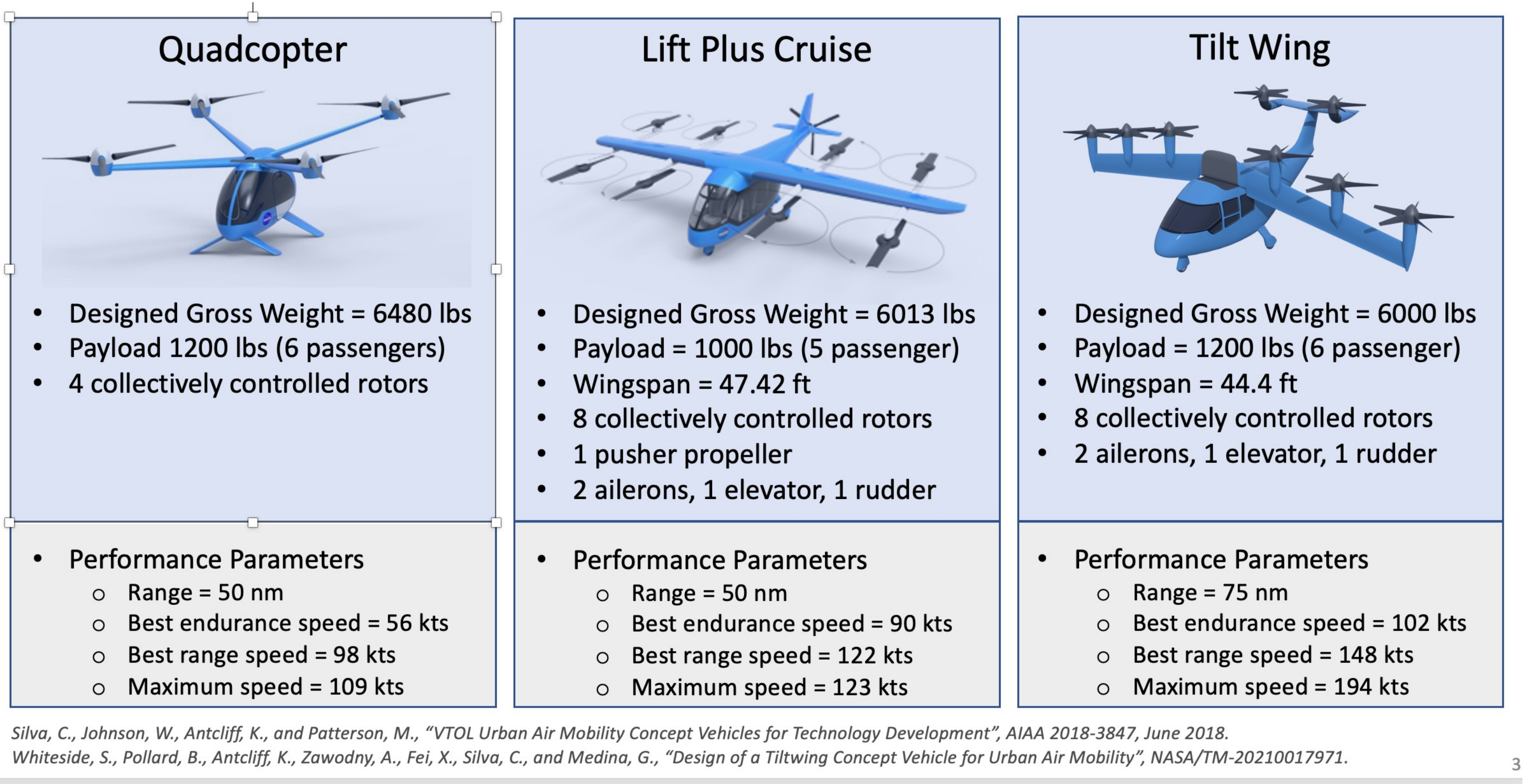
Revolutionary Vertical Lift Technology Project

- **Research Activities**
- Clean and Efficient Propulsion
- Efficient and Quiet Vehicles
- Safety, Comfort and Accessibility
- Modeling/Simulation and Test Capability

- Reference: Revolutionary Vertical Lift Technology Project Overview (nasa.gov)



Program Background: RVLT test vehicles



Quadcopter

- Designed Gross Weight = 6480 lbs
- Payload 1200 lbs (6 passengers)
- 4 collectively controlled rotors

- Performance Parameters
  - Range = 50 nm
  - Best endurance speed = 56 kts
  - Best range speed = 98 kts
  - Maximum speed = 109 kts

Lift Plus Cruise

- Designed Gross Weight = 6013 lbs
- Payload = 1000 lbs (5 passenger)
- Wingspan = 47.42 ft
- 8 collectively controlled rotors
- 1 pusher propeller
- 2 ailerons, 1 elevator, 1 rudder

- Performance Parameters
  - Range = 50 nm
  - Best endurance speed = 90 kts
  - Best range speed = 122 kts
  - Maximum speed = 123 kts

Tilt Wing

- Designed Gross Weight = 6000 lbs
- Payload = 1200 lbs (6 passenger)
- Wingspan = 44.4 ft
- 8 collectively controlled rotors
- 2 ailerons, 1 elevator, 1 rudder

- Performance Parameters
  - Range = 75 nm
  - Best endurance speed = 102 kts
  - Best range speed = 148 kts
  - Maximum speed = 194 kts

Silva, C., Johnson, W., Antcliff, K., and Patterson, M., "VTOL Urban Air Mobility Concept Vehicles for Technology Development", AIAA 2018-3847, June 2018.
Whiteside, S., Pollard, B., Antcliff, K., Zawodny, A., Fei, X., Silva, C., and Medina, G., "Design of a Tiltwing Concept Vehicle for Urban Air Mobility", NASA/TM-20210017971.

eVTOL Flight Challenges

- **Diversity in Proposed Aircraft**

- Powered Lift (e.g., Winged eVTOL) have additional challenges in transition
  - Operations in Low speed and Hover will be restricted for many candidate eVTOL aircraft due to lack cyclic and/or collective control

- <u>Automation</u> proposed to help with these challenges

- <u>All concepts currently proposing Indirect Flight Controls (IFCS)</u>
  - See Kaneshige et. al in MST-03 for development

- <u>Existing Means of Compliance Inadequate for IFCS and increasing automated functions</u>
  - IFCS airplanes have only certified under Special Conditions
- <u>Evaluation methods</u> will need to cross airworthiness and operations

- Need for industry representative VTOL aircraft and automation for developing and as baseline evaluation methods

Beta ALIA-250
(Lift + Cruise)

Joby S4 (Tilt Rotor)

Lilium Jet (Tilt Ducted Electric Fans) [Vectored Thrust]

Archer Maker
(Tilt Rotor Hybrid)

Wisk Cora (Lift + Cruise, tilt rotor Hybrid)

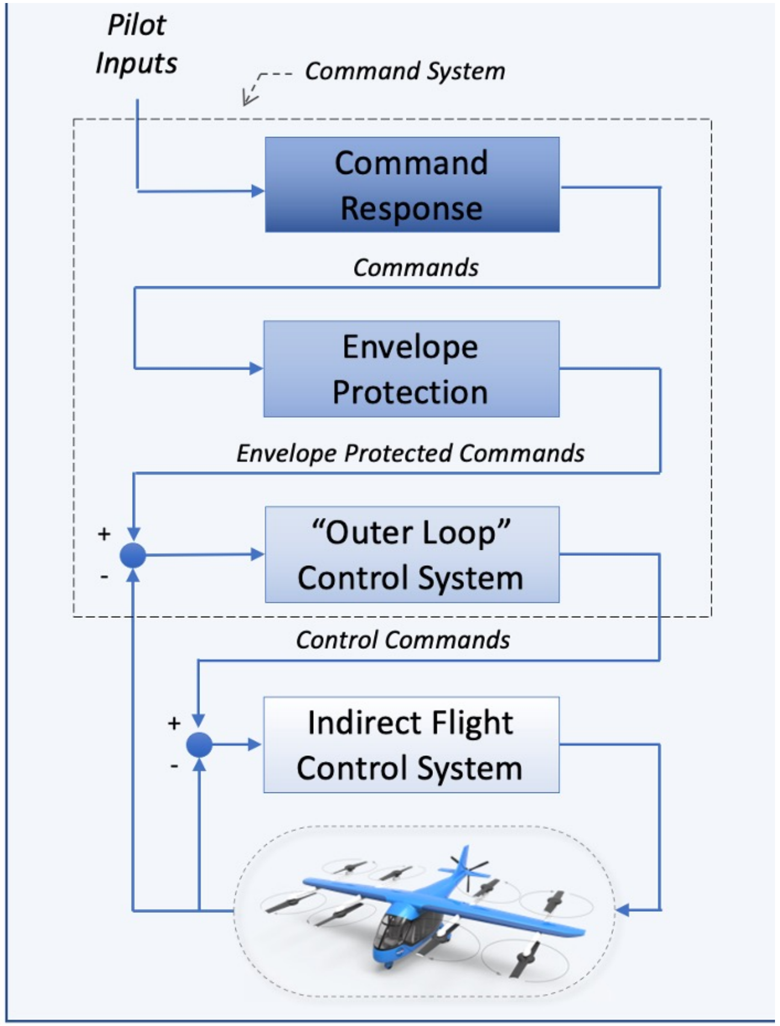
Photos courtesy of Vertical Flight Society, 2023

Reflection on Indirect Flight Control

- A common approach to mitigate these challenges for many eVTOL concepts is the use of Indirect Flight Control Systems (IFCS), commonly referred to as “Fly-by-Wire” or FBW.
- IFCS replace mechanical linkages between the pilot and flight control surfaces with electrical signals that are interpretations of the pilot actions by an onboard computer. These signals are sent to actuators at the control surfaces.
- In addition to IFCS providing reduced weight and reliability advantages, the
  - adoption of IFCS has been used to enhance stability, maneuverability and controllability of aircraft and
  - has enabled the development of automation and safety functions (e.g., envelope protection).

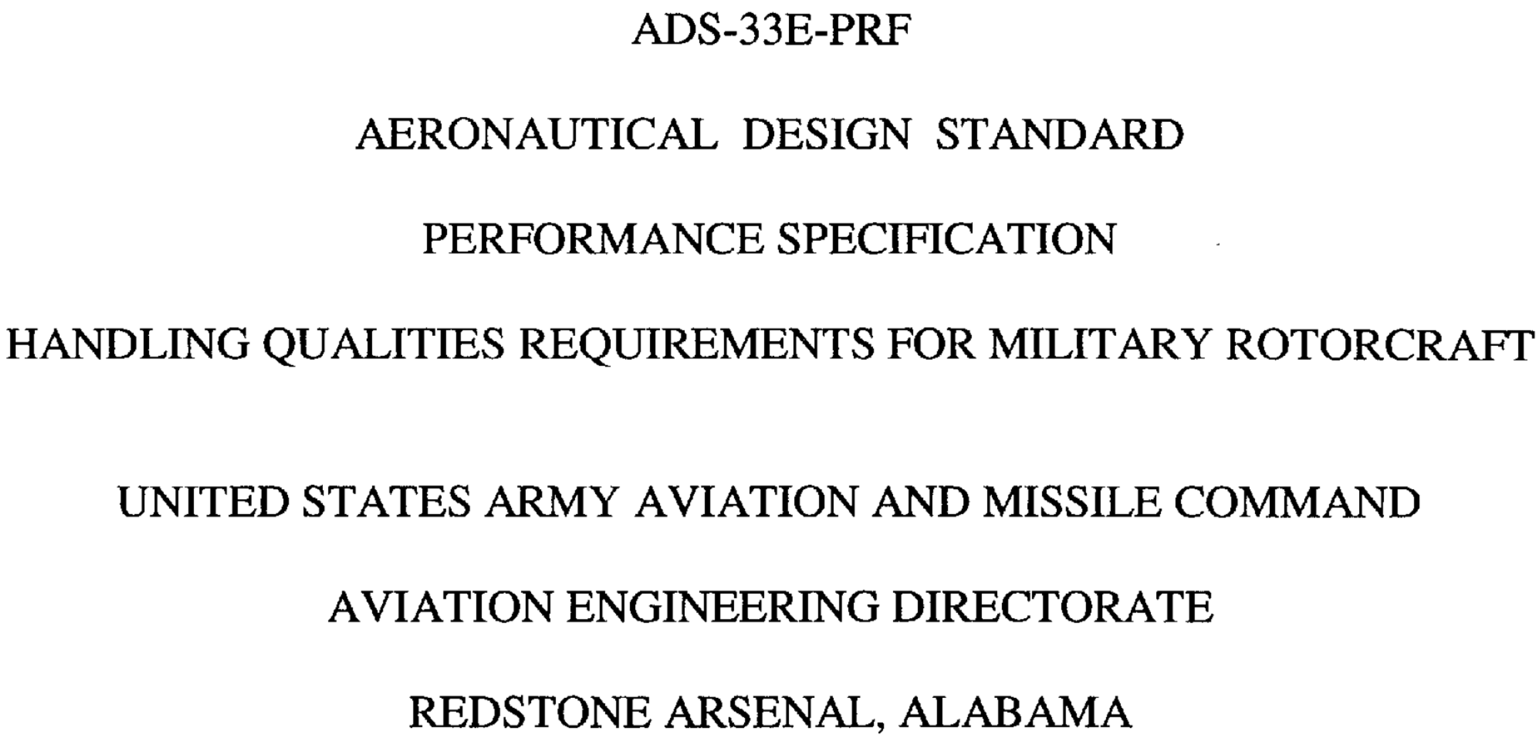
Simplified Vehicle Control (SVC) System

- **Command System**
  - Command Response translates inceptor inputs into vertical, lateral, directional and speed commands
    - Commands are described by their command response type
  - Envelope protection limits commands to maintain a stable flight envelope
  - Outer loop control system computes rotational and translational control commands for the current lifting mode
    - Rotational control commands: pitch rate, roll rate, yaw rate
    - Translational commands: (body-axis) vertical velocity, (stability-axis) longitudinal acceleration
- **Indirect Flight Control System**
  - Provides inner loop stability and control augmentation
  - Generates pitch, roll, yaw, heave and thrust commands



Kaneshige, J., Lombaerts, T., Shish, K., and Feary, M., "Command and Control Concepts for a Lift Plus Cruise Electric Vertical Takeoff and Landing Vehicle", AIAA 2023-3910, June 2023.

History - Aeronautical Design Standard – 33



ADS-33E-PRF

AERONAUTICAL DESIGN STANDARD

PERFORMANCE SPECIFICATION

HANDLING QUALITIES REQUIREMENTS FOR MILITARY ROTORCRAFT

UNITED STATES ARMY AVIATION AND MISSILE COMMAND

AVIATION ENGINEERING DIRECTORATE

REDSTONE ARSENAL, ALABAMA

Rationale - Adaptation of ADS -33 For eVTOL

Why ADS-33?

An examination of methods to help sort through the diversity and complexity of AAM aircraft and automation configurations led to a method developed by the US Army and NASA referred to as Aeronautical Design Standard-33 (ADS-33).

History

- ADS-33 was developed in the 1970's to support the evaluation of the U.S. Army's Light Helicopter Experimental (LHX) program. The Comanche RAH-66 development was a result of the LHX program.

- The LHX program and Comanche helicopter had several innovations including
  - A digital Fly-By-Wire flight control system (Indirect Flight Control System)
  - Proposals for novel inceptor configurations.

- The standard describes methods for:
  - the flight test and analysis of aircraft handling characteristics,
  - the method provides a basis for developing flight test maneuvers based on mission requirements, referred to as Mission Task Elements.
  - Introduced the Useable Cue Environment (UCE)

History: ADS-33 – LHX Program = Comanche

- ADS-33 was developed in the 1970’s to support the evaluation of the U.S. Army’s Light Helicopter Experimental (LHX) program.

Comanche surrogate (Sikorsky)

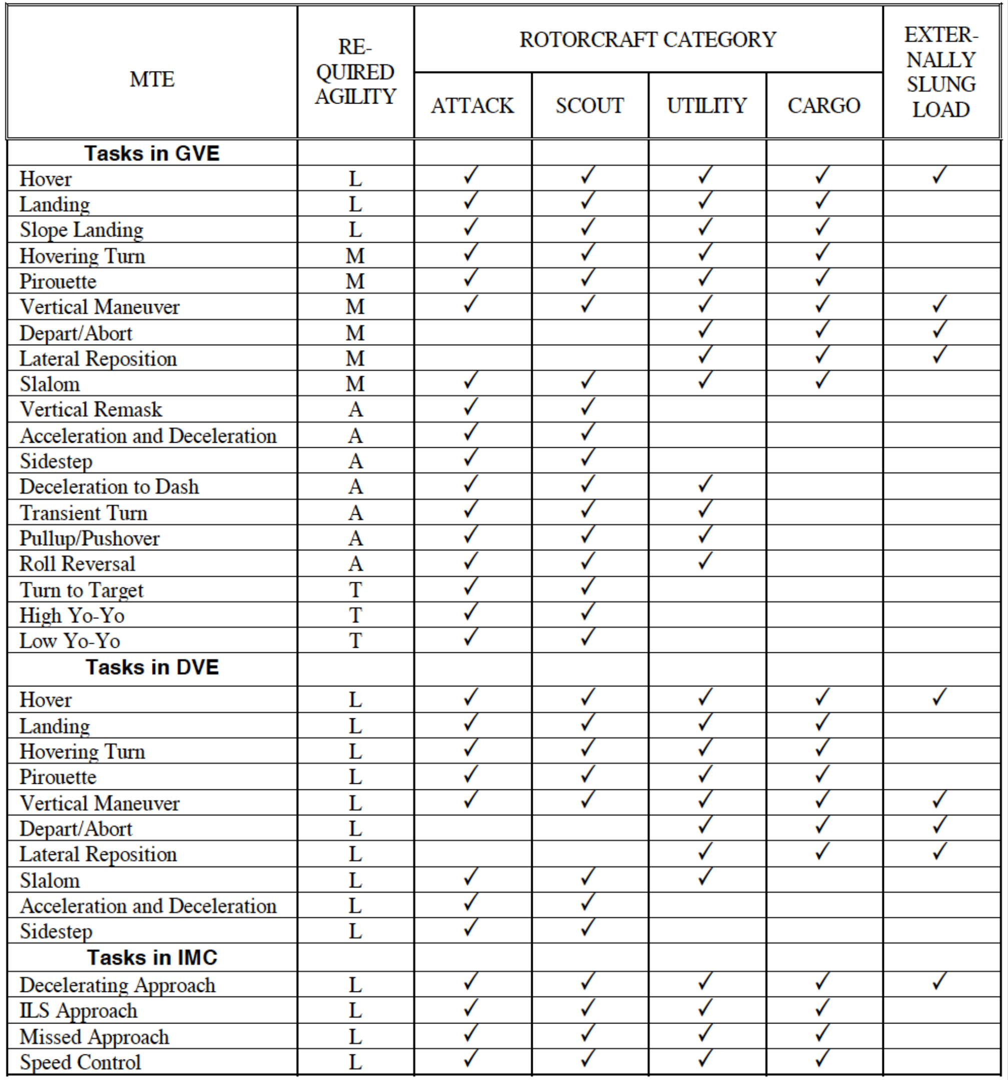
RAH-66 Comanche prototype

Rationale: ADS-33 Mission - Task – Element Approach

- Mission Task Elements (MTE) developed by the US Army for evaluating military rotorcraft.
  - MTEs enable <u>evaluation by mission</u> rather than aircraft type or configuration.
- The set of maneuvers described in ADS-33E provided a basis for the Flight Test Maneuvers for
  - Focus on the <u>defining the Mission/Operational Concept</u>
  - <u>Determine performance criteria</u>
- Criteria do not change for the different vehicle configurations or <u>automation</u> within a category
- Criteria do not change for varying <u>automation capabilities</u> or configuration
  - Scalable from today's operational concept for a few operators to operate many vehicles (m:N)


Precision


Aggressiveness



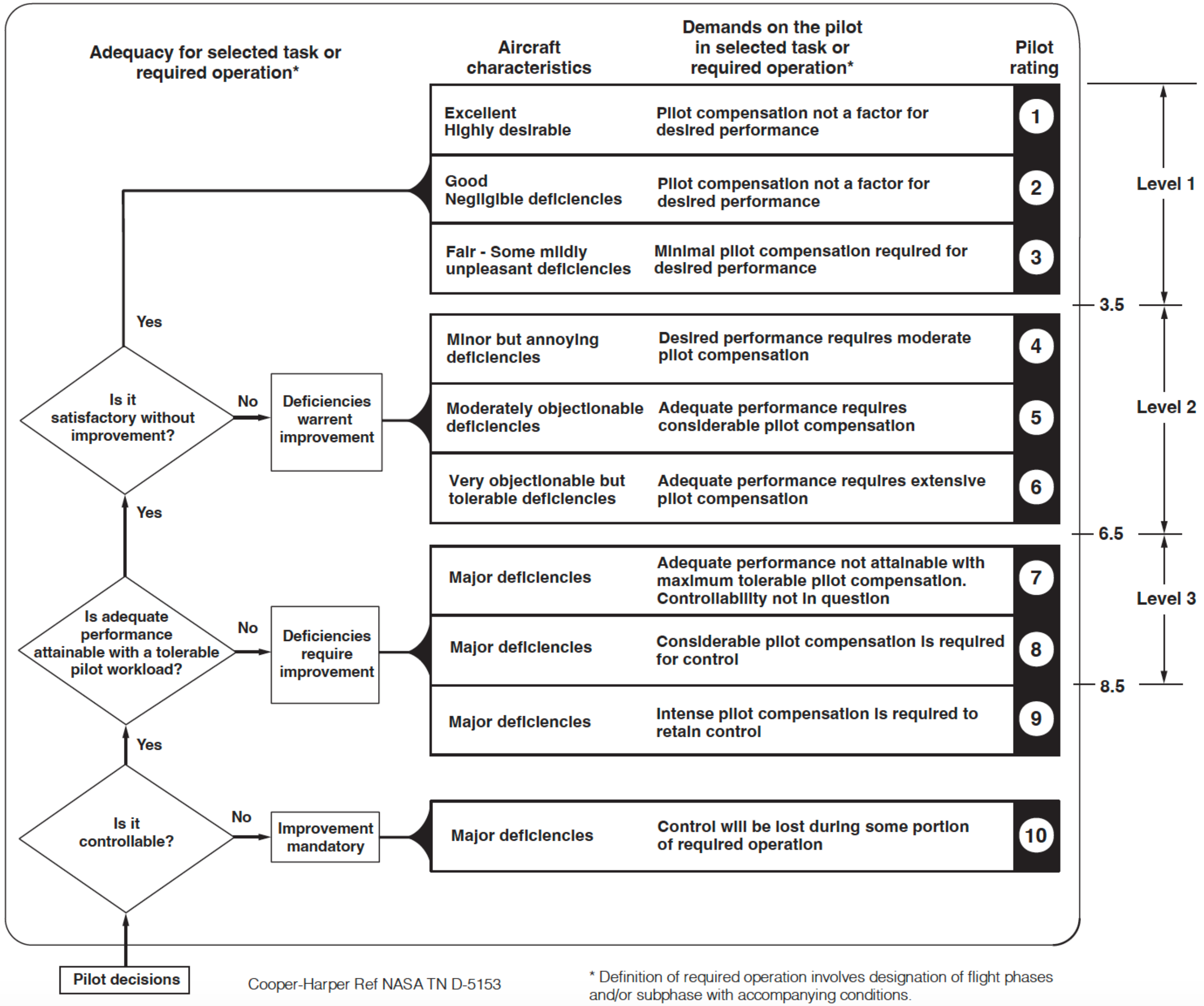
MTE	REQUIRED AGILITY	ROTORCRAFT CATEGORY				EXTERNALLY SLUNG LOAD
		ATTACK	SCOUT	UTILITY	CARGO	
Tasks in GVE						
Hover	L	✓	✓	✓	✓	✓
Landing	L	✓	✓	✓	✓	
Slope Landing	L	✓	✓	✓	✓	
Hovering Turn	M	✓	✓	✓	✓	
Pirouette	M	✓	✓	✓	✓	
Vertical Maneuver	M	✓	✓	✓	✓	✓
Depart/Abort	M			✓	✓	✓
Lateral Reposition	M			✓	✓	✓
Slalom	M	✓	✓	✓	✓	
Vertical Remask	A	✓	✓			
Acceleration and Deceleration	A	✓	✓			
Sidestep	A	✓	✓			
Deceleration to Dash	A	✓	✓	✓		
Transient Turn	A	✓	✓	✓		
Pullup/Pushover	A	✓	✓	✓		
Roll Reversal	A	✓	✓	✓		
Turn to Target	T	✓	✓			
High Yo-Yo	T	✓	✓			
Low Yo-Yo	T	✓	✓			
Tasks in DVE						
Hover	L	✓	✓	✓	✓	✓
Landing	L	✓	✓	✓	✓	
Hovering Turn	L	✓	✓	✓	✓	
Pirouette	L	✓	✓	✓	✓	
Vertical Maneuver	L	✓	✓	✓	✓	✓
Depart/Abort	L			✓	✓	✓
Lateral Reposition	L			✓	✓	✓
Slalom	L	✓	✓	✓		
Acceleration and Deceleration	L	✓	✓			
Sidestep	L	✓	✓			
Tasks in IMC						
Decelerating Approach	L	✓	✓	✓	✓	✓
ILS Approach	L	✓	✓	✓	✓	
Missed Approach	L	✓	✓	✓	✓	
Speed Control	L	✓	✓	✓	✓	

MTE maneuvers, ADS-33E-PRF (1996)

Handling Quality Rating (HQR) Scale

Test Pilots use the Cooper-Harper Handling Qualities Rating (HQR) Scale to assess the workload and task performance required to perform designed MTEs.

Note – Think about the play between performance and pilot compensation for automated control.



Adequacy for selected task or required operation*

Pilot decisions

Is it controllable? — No → Improvement mandatory — Yes →

Is adequate performance attainable with a tolerable pilot workload? — No → Deficiencies require improvement — Yes →

Is it satisfactory without improvement? — No → Deficiencies warrent improvement — Yes →

Aircraft characteristics	Demands on the pilot in selected task or required operation*	Pilot rating	
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1	Level 1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2	
Fair - Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3	
			3.5
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4	Level 2
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5	
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6	
			6.5
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7	Level 3
Major deficiencies	Considerable pilot compensation is required for control	8	
Major deficiencies	Intense pilot compensation is required to retain control	9	
			8.5
Major deficiencies	Control will be lost during some portion of required operation	10	

Cooper-Harper Ref NASA TN D-5153

* Definition of required operation involves designation of flight phases and/or subphase with accompanying conditions.

Flight Test Tasks (FTT)

- Flight Test Tasks (FTT) is the civilian term for MTEs
- Catalog of FT Maneuvers' were developed for military evaluation of IFCS and advanced automated control as an FAA Means of Compliance.

- Maneuvers and Performance Criteria are based on expected Concept of Operations and expected Environmental Conditions

- Maneuvers are designed to:
    - Expose deficiencies in aircraft controllability
    - Be agnostic to aircraft and automation configuration (including inceptors)
    - Stress test aircraft and automation configuration in operationally representative maneuvers

Vertical Reposition	Pirouette	Heliport Approach	Decelerating Turn	Balked Landing/Missed Approach	Hazard Avoidance
VR	**P**	**HA**	**DT**	**BL** **MA**	**HA_2**
HT	**LR**	**PH**	**RT**	**OA**	S
Hovering Turn	Lateral Reposition	Precision Hover	Rejected Takeoff	Offset Approach	Slalom

ADS -33 Lessons

- The initial research efforts validated the use of the MTE approach described in ADS-33 as useful framework for evaluating different levels of automated systems on aircraft and assessing the wide variety of novel AAM aircraft configurations being proposed.
- The Flight Test maneuvers developed from the research effort are a starting point for a new Means of Compliance for the evaluation of handling qualities for the new Powered Lift class of aircraft.
- The associated performance criteria needs be designed to align with the expected requirements of AAM operations and infrastructure.
- Use of the ADS-33 methodology also highlighted the requirement to clearly define operational concept details to precisely define maneuver performance requirements.
- The definitions and an understanding of the operational environment were critical to successful automation Design and evaluation and relied upon accurate definition of the mission objectives and an understanding of the operational environment.

AEP-1 Study

- The focus of the AEP-1 study was an evaluation of the ability of three selected Flight Test Maneuvers to assess different industry representative command and pilot interface concepts using an industry representative eVTOL (i.e. Lift-Plus-Cruise) aircraft model.

- A particular area of focus for the FAA and NASA sponsored studies is the assessment of handling qualities during transitions. There are many different types of transitions that are likely to cause handling deficiencies and Pilot Induced Oscillations (PIO), including transitions across:

  - Lift mode: Thrust-borne, Semi-thrust borne, Semi-Wing borne or Wing-borne lift
  - Reference Frame: Body Axis, Airmass, Earth-referenced
  - Envelope protection boundary and recovery
  - Control Modes and Response Types
  - Inceptor behavior
  - Display and alerting behavior

Automation Enabled Pilot Study 1 (AEP-1)

- **Study Requirements:**
  - Simulation environment for AAM operations (Out-The-Window, Inceptors, Cockpit Displays)
  - Industry representative VTOL aircraft and aircraft automation configurations
  - Flight Task Elements (ADS-33 MTEs)

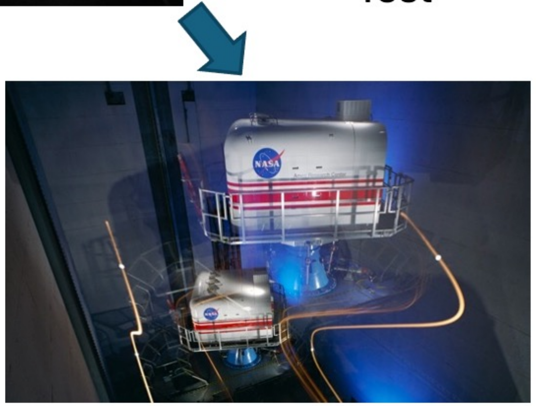
- **Method**
  - Remote capability required during the pandemic including new OTW for home testing
  - Automation framework to characterize automation configurations
  - Fixed-Base simulator for development test and training
  - Evaluation in Vertical Motion Simulator (VMS)

- **Data Collection Participants**
  - 6 formally trained and experienced test pilots (all had VTOL and powered lift experience)
  - 4 from extensive rotary wing background
  - 2 from fixed wing background

Quadcopter Lift Plus Cruise

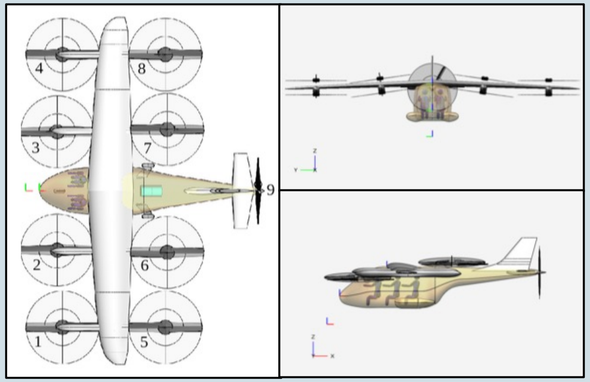
Desktop Development

Fixed-Base Development and Test



AEP-1 Study: Lift Plus Cruise (LPC) Concept Vehicle

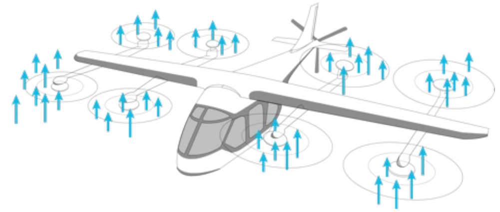
Lift Plus Cruise



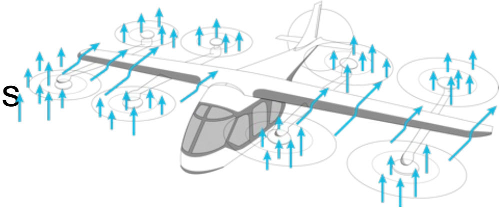
- Design Parameters
    - Gross Weight = 6013 lbs
    - Payload = 1000 lbs (5 passenger)
    - Wingspan = 47.42 ft
    - 8 collectively controlled rotors
    - 1 pusher propeller
    - 2 ailerons, 1 elevator, 1 rudder
- Performance Parameters
    - Range = 50 nm
    - Best endurance speed = 90 kts
    - Best range speed = 122 kts
    - Maximum speed = 123 kts

LPC Winged eVTOL Taxonomy

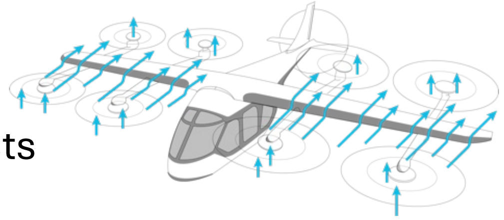
- Thrust Borne Lift (0-20 KIAS)
    - Rotors provide lift
    - Airframe produces minimal aerodynamic effects



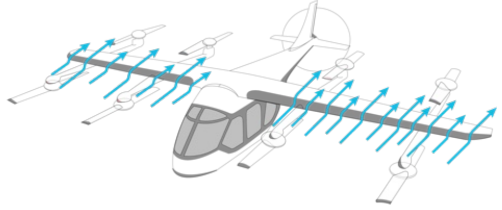
- Semi-Thrust Borne Lift (15-40 KIAS)
    - Rotors provide primary lift
    - Airframe produces moderate aerodynamic effects (i.e., requiring AoA and sideslip considerations)



- Semi-Wing Borne Lift (30-100 KIAS)
    - Airframe provides primary lift
    - Rotors provide some lift (e.g., for AoA protection)
    - Airframe produces significant aerodynamic effects (i.e., requiring AoA and sideslip protection)

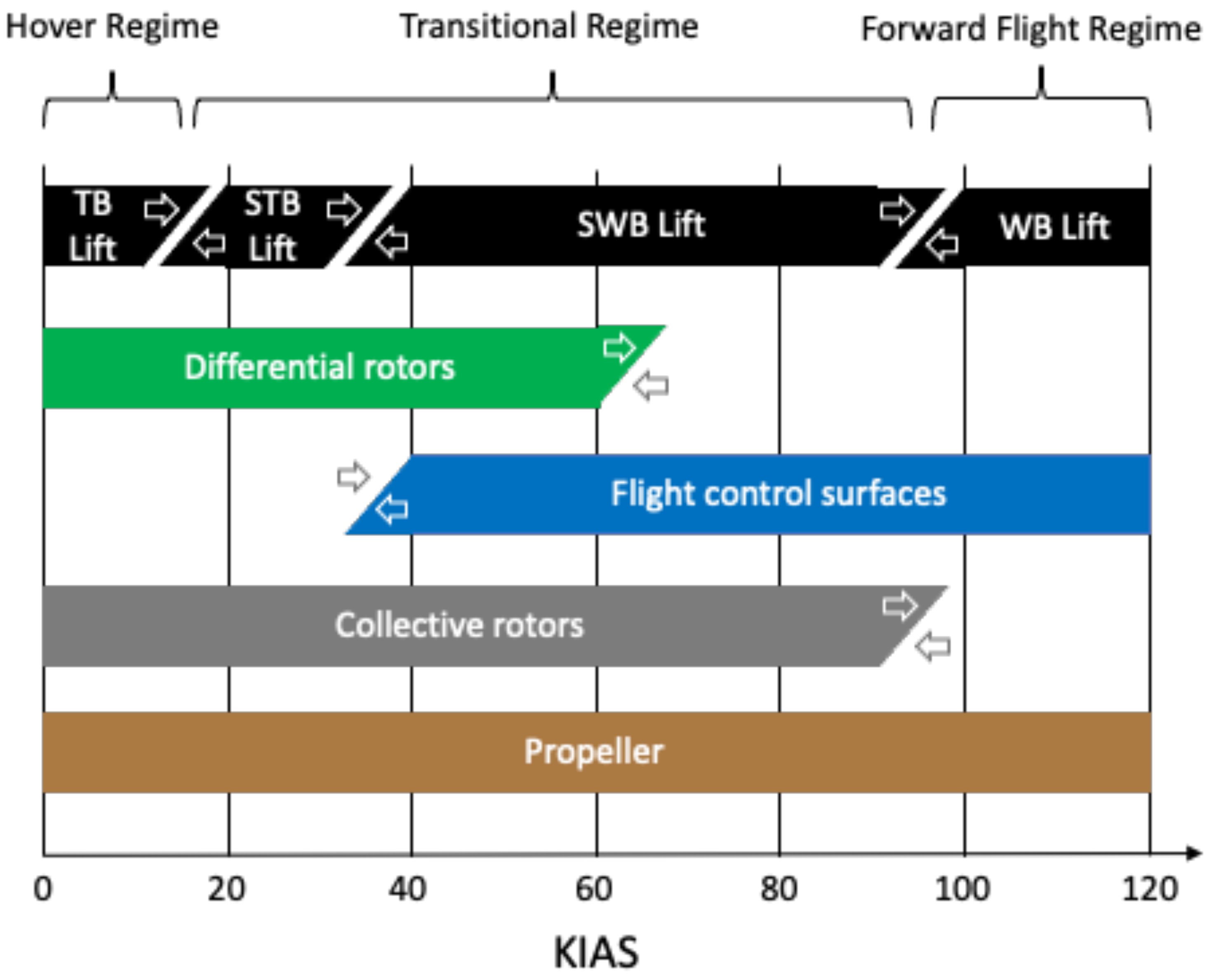


- Wing Borne Lift (90-120 KIAS)
    - Airframe provides lift
    - Rotors are stopped

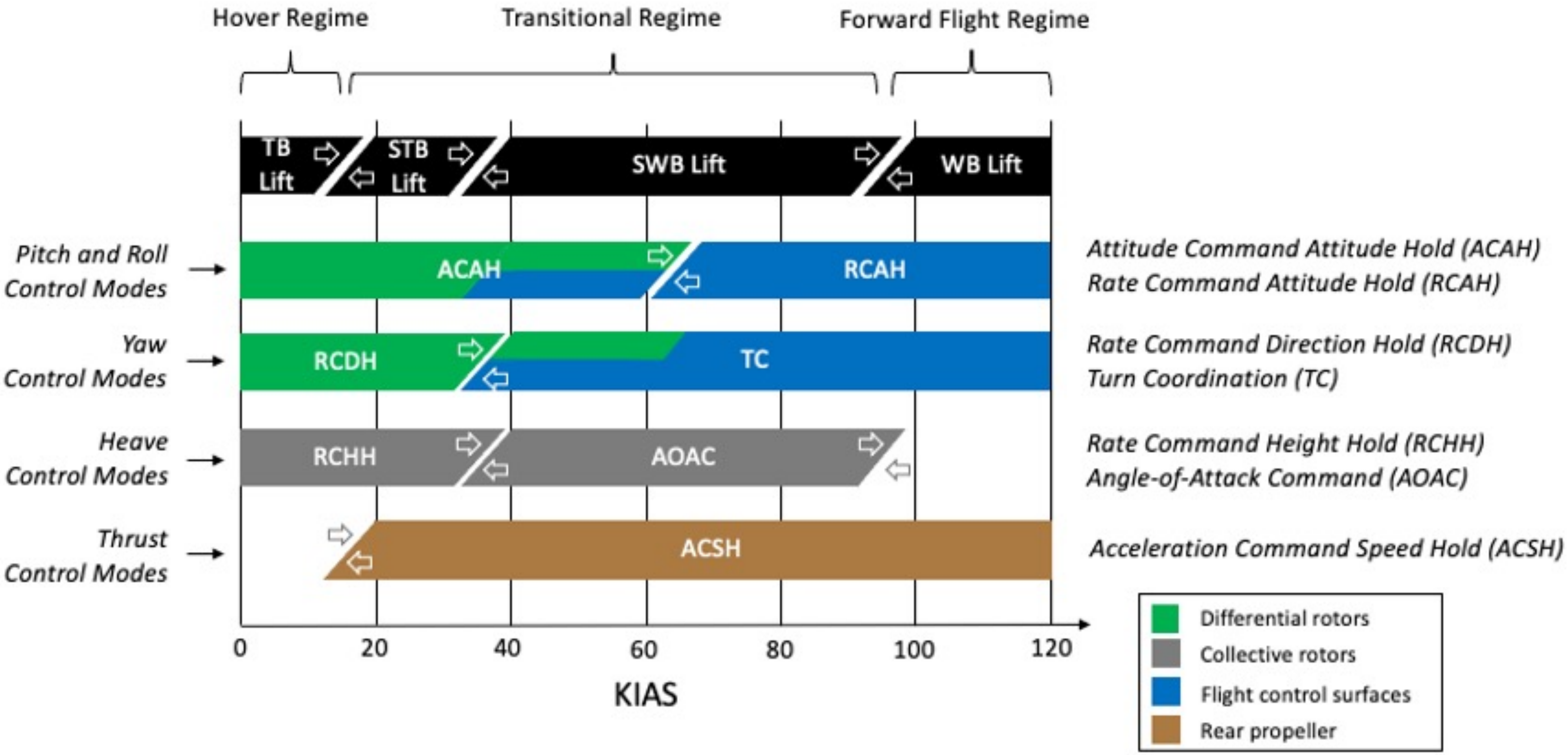


Silva, C., Johnson, W., Antcliff, K., and Patterson, M., "VTOL Urban Air Mobility Concept Vehicles for Technology Development", AIAA 2018-3847, June 2018.
Advanced Rotorcraft Technology, Inc., "Improved Fidelity Simulation Models for VTOL Concept Vehicles", SBIR Phase III 80NSSC21C0610 Progress Report No. 3, May 2022.

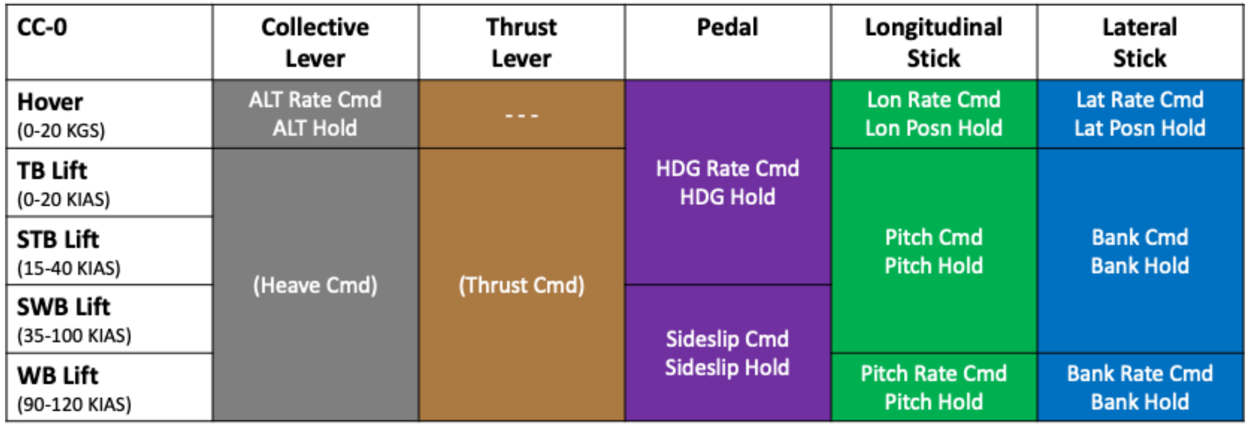
AEP-1 LPC Control Allocation Schedule



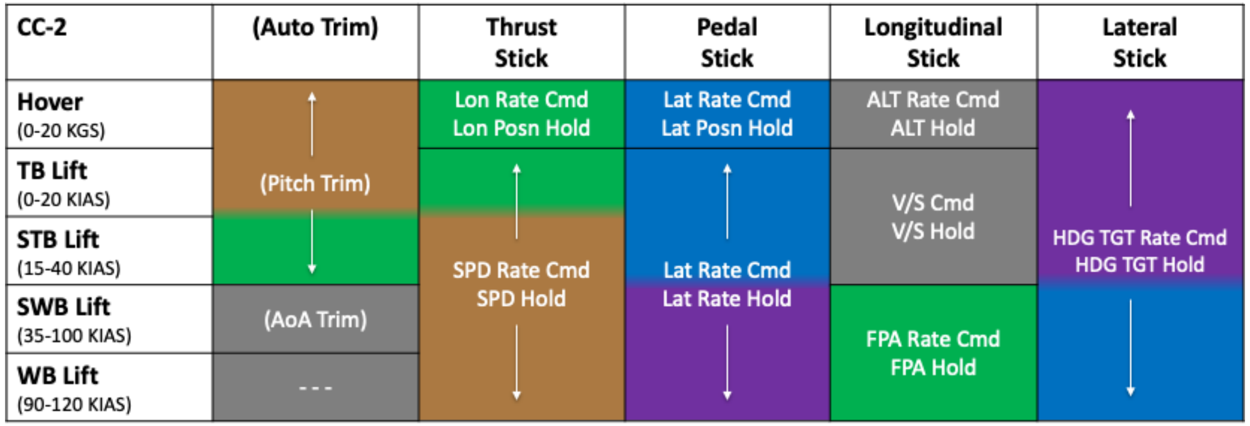
AEP-1 LPC Control Mode Schedule



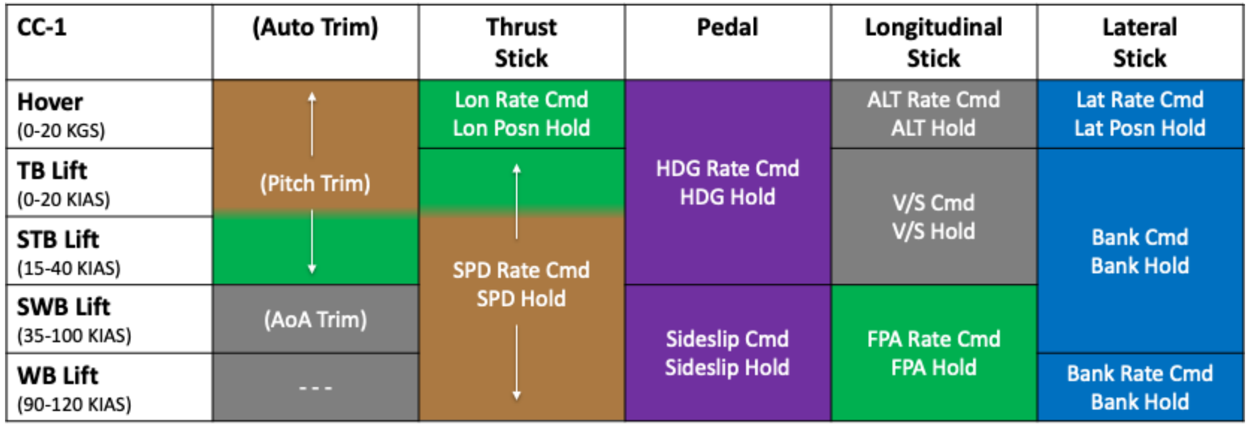
AEP-1 LPC Command Concept Response Types



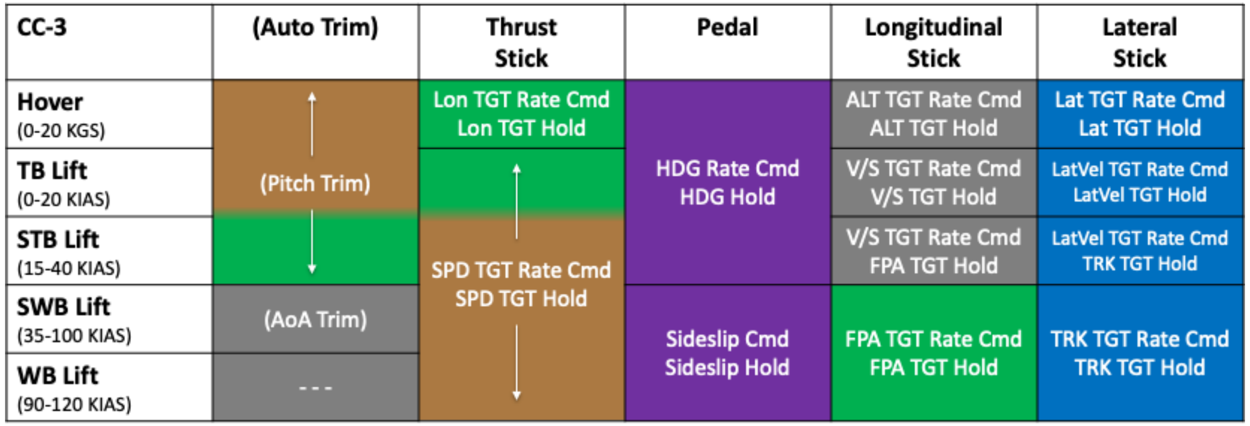
CC-0	Collective Lever	Thrust Lever	Pedal	Longitudinal Stick	Lateral Stick
Hover (0-20 KGS)	ALT Rate Cmd ALT Hold	- - -	HDG Rate Cmd HDG Hold	Lon Rate Cmd Lon Posn Hold	Lat Rate Cmd Lat Posn Hold
TB Lift (0-20 KIAS)	(Heave Cmd)	(Thrust Cmd)		Pitch Cmd Pitch Hold	Bank Cmd Bank Hold
STB Lift (15-40 KIAS)					
SWB Lift (35-100 KIAS)			Sideslip Cmd Sideslip Hold		
WB Lift (90-120 KIAS)				Pitch Rate Cmd Pitch Hold	Bank Rate Cmd Bank Hold



CC-2	(Auto Trim)	Thrust Stick	Pedal Stick	Longitudinal Stick	Lateral Stick
Hover (0-20 KGS)	(Pitch Trim)	Lon Rate Cmd Lon Posn Hold	Lat Rate Cmd Lat Posn Hold	ALT Rate Cmd ALT Hold	HDG TGT Rate Cmd HDG TGT Hold
TB Lift (0-20 KIAS)		SPD Rate Cmd SPD Hold	Lat Rate Cmd Lat Rate Hold	V/S Cmd V/S Hold	
STB Lift (15-40 KIAS)					
SWB Lift (35-100 KIAS)	(AoA Trim)			FPA Rate Cmd FPA Hold	
WB Lift (90-120 KIAS)	- - -				



CC-1	(Auto Trim)	Thrust Stick	Pedal	Longitudinal Stick	Lateral Stick
Hover (0-20 KGS)	(Pitch Trim)	Lon Rate Cmd Lon Posn Hold	HDG Rate Cmd HDG Hold	ALT Rate Cmd ALT Hold	Lat Rate Cmd Lat Posn Hold
TB Lift (0-20 KIAS)		SPD Rate Cmd SPD Hold		V/S Cmd V/S Hold	Bank Cmd Bank Hold
STB Lift (15-40 KIAS)					
SWB Lift (35-100 KIAS)	(AoA Trim)		Sideslip Cmd Sideslip Hold	FPA Rate Cmd FPA Hold	
WB Lift (90-120 KIAS)	- - -				Bank Rate Cmd Bank Hold

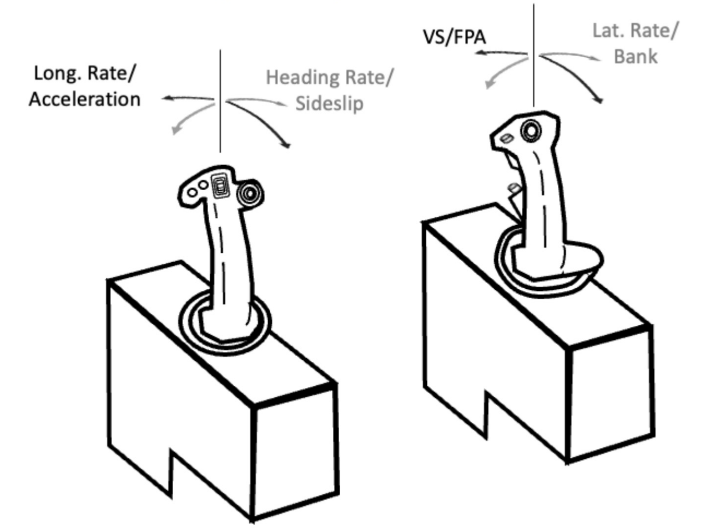


CC-3	(Auto Trim)	Thrust Stick	Pedal	Longitudinal Stick	Lateral Stick
Hover (0-20 KGS)	(Pitch Trim)	Lon TGT Rate Cmd Lon TGT Hold	HDG Rate Cmd HDG Hold	ALT TGT Rate Cmd ALT TGT Hold	Lat TGT Rate Cmd Lat TGT Hold
TB Lift (0-20 KIAS)		SPD TGT Rate Cmd SPD TGT Hold		V/S TGT Rate Cmd V/S TGT Hold	LatVel TGT Rate Cmd LatVel TGT Hold
STB Lift (15-40 KIAS)				V/S TGT Rate Cmd FPA TGT Hold	LatVel TGT Rate Cmd TRK TGT Hold
SWB Lift (35-100 KIAS)	(AoA Trim)		Sideslip Cmd Sideslip Hold	FPA TGT Rate Cmd FPA TGT Hold	TRK TGT Rate Cmd TRK TGT Hold
WB Lift (90-120 KIAS)	- - -				

Axes of Control: ■ Heave Axis ■ Thrust Axis ■ Yaw Axis ■ Pitch Axis ■ Roll Axis

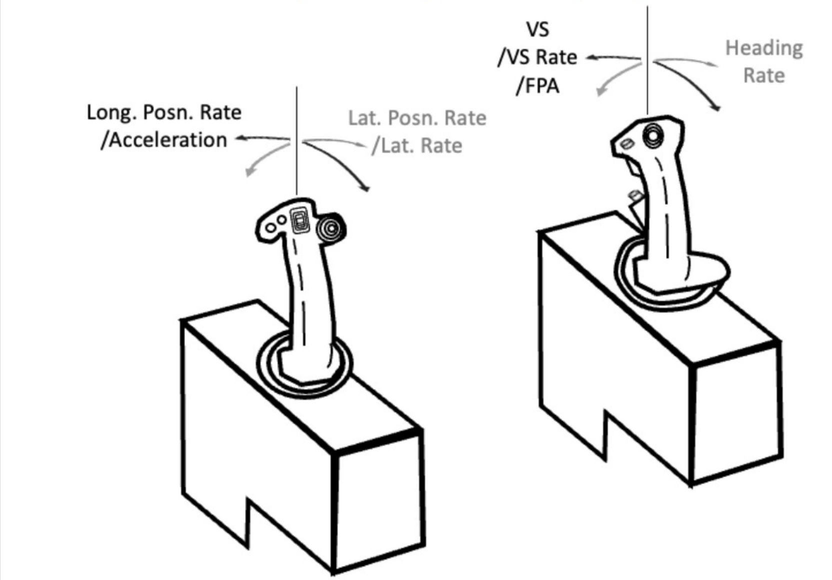
AEP-1 Inceptor Configurations

Inceptor Configuration- 1 (IC-1)



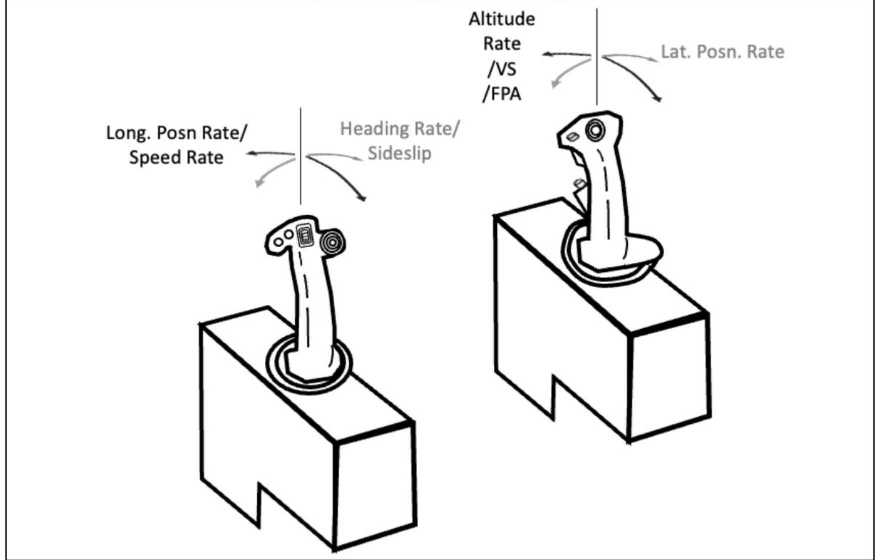
2+2 Rate
Right Inceptor = Vertical Speed/FPA Rate and Lateral Rate/Bank
Left Inceptor = Longitudinal Rate Command/Acceleration and Heading Rate/Sideslip
Flight control access descriptions are in different shades of gray to reflect the different axes.

Inceptor Configuration- 2 (IC-2)



2+2 Rate
Right Inceptor = Vertical Speed/FPA Rate and Heading Rate
Left Inceptor = Longitudinal Position/Rate or Acceleration and Lateral Rate/Position Rate

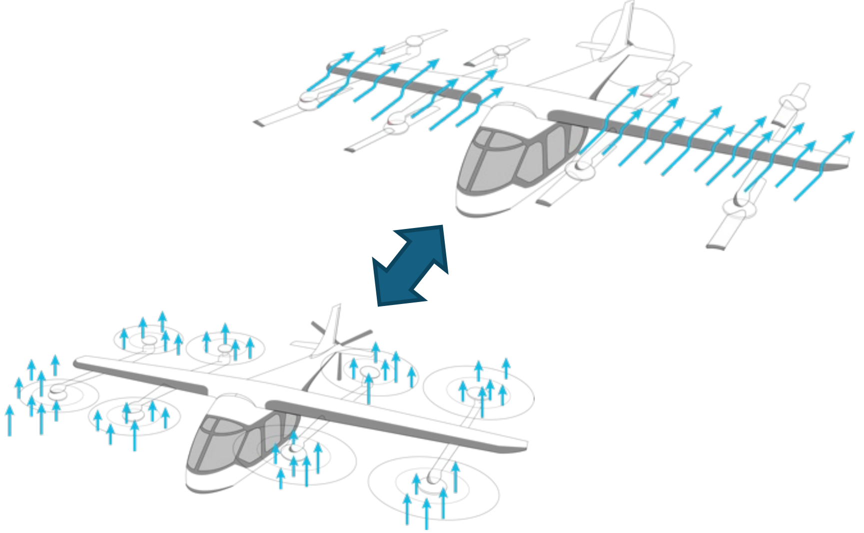
Inceptor Configuration- 3 (IC-3)

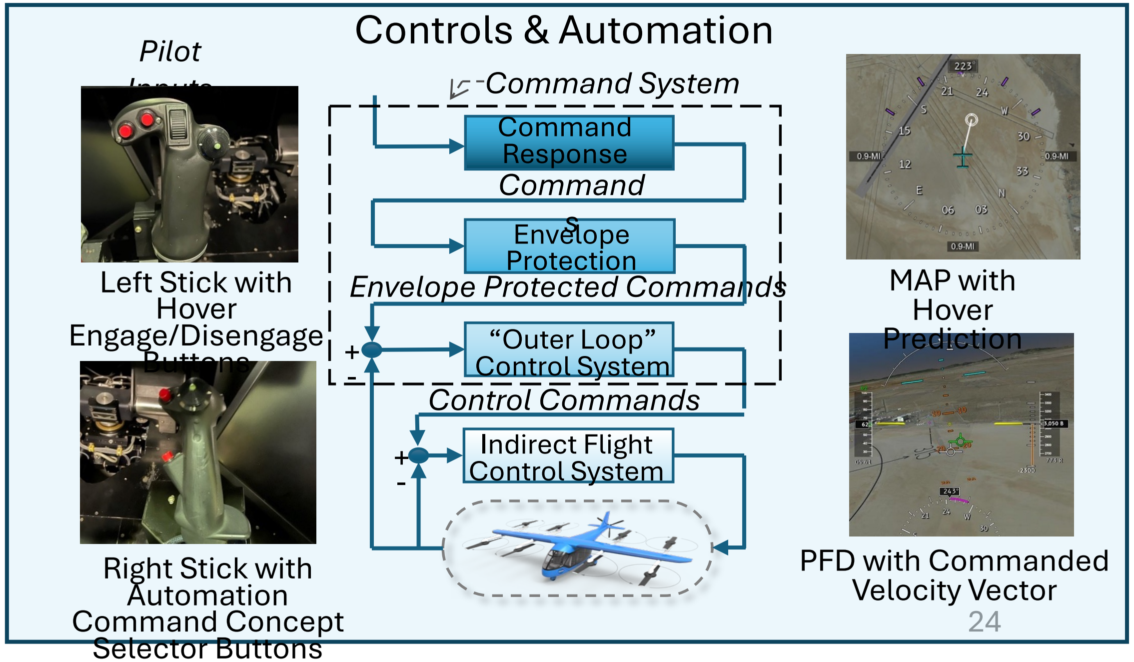


2+2 Rate
Right Inceptor = Altitude Rate/Vertical Speed/FPA Rate and Lateral Position Rate
Left Inceptor = Longitudinal Position Rate or Speed Rate and Heading Rate or Sideslip

Winged VTOL Automation Behavior Considerations

- **Lift – Mode Transitions**
  - Thrust <> Semi-Thrust <> Semi-wing <> Wing Born lift source
- **Reference frames**
  - Earth/Airmass/Body frame
- **Command (CS) and Response Types (RT) and RT combinations**
  - e.g., CS: Rate vs. attitude
  - e.g., RT: Heading and altitude hold
- **Flight Control Modes**
  - Ground, Hover, Velocity
- **Pilot Interfaces beyond IFCS**
  - Information integration and alerting
- **Envelope protection**
  - Behavior at transitions





Controls & Automation

Pilot Inputs

Command System

Command Response

Commands

Envelope Protection

Envelope Protected Commands

“Outer Loop” Control System

Control Commands

Indirect Flight Control System

Left Stick with Hover Engage/Disengage Buttons

Right Stick with Automation Command Concept Selector Buttons

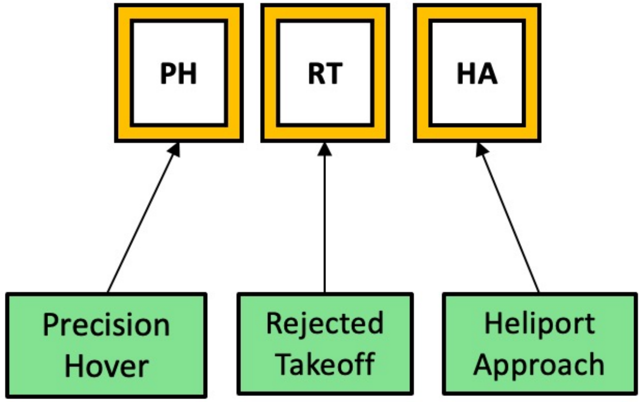
MAP with Hover Prediction

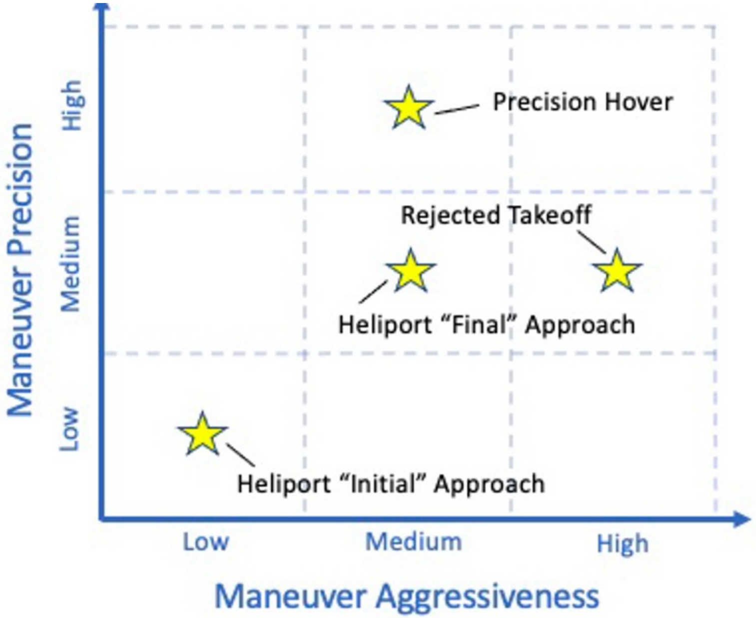
PFD with Commanded Velocity Vector

AEP-1 Study

Test points

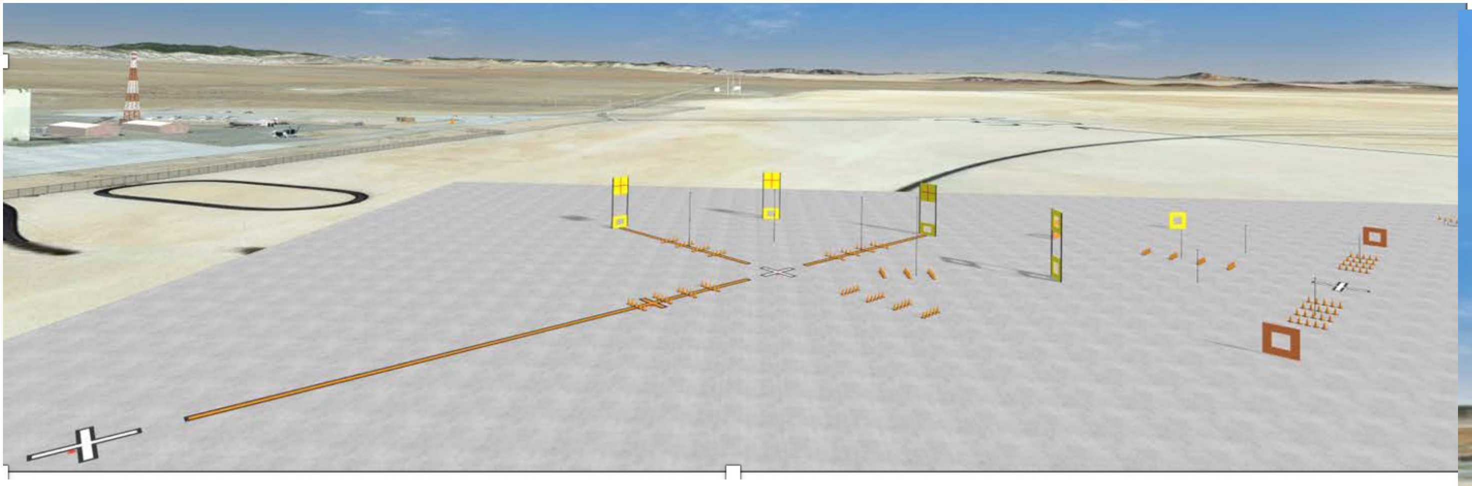
- 102 data points collected
  - 3 industry representative Automation Configurations (Command Concepts -1, -2, -3)
  - 3 Maneuvers were selected (Precision Hover, Rejected Takeoff, Heliport Approach). The Precision Hover maneuver was chosen to highlight the effects of different levels of augmentation with the LPC handling characteristics. The Rejected Takeoff and Heliport Approach maneuvers were chosen to investigate the automation behavior during transitional flight.
  - 2 wind conditions (calm, 17 knot wind)



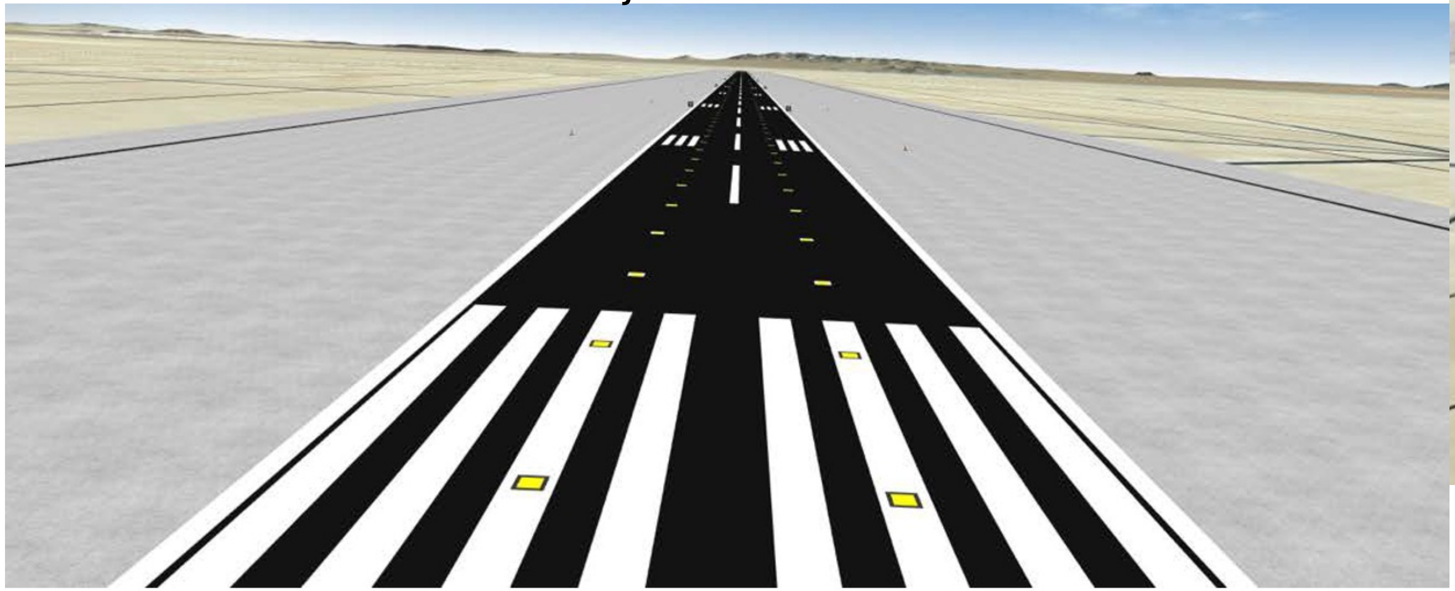


AEP-1 simulated course examples with furniture

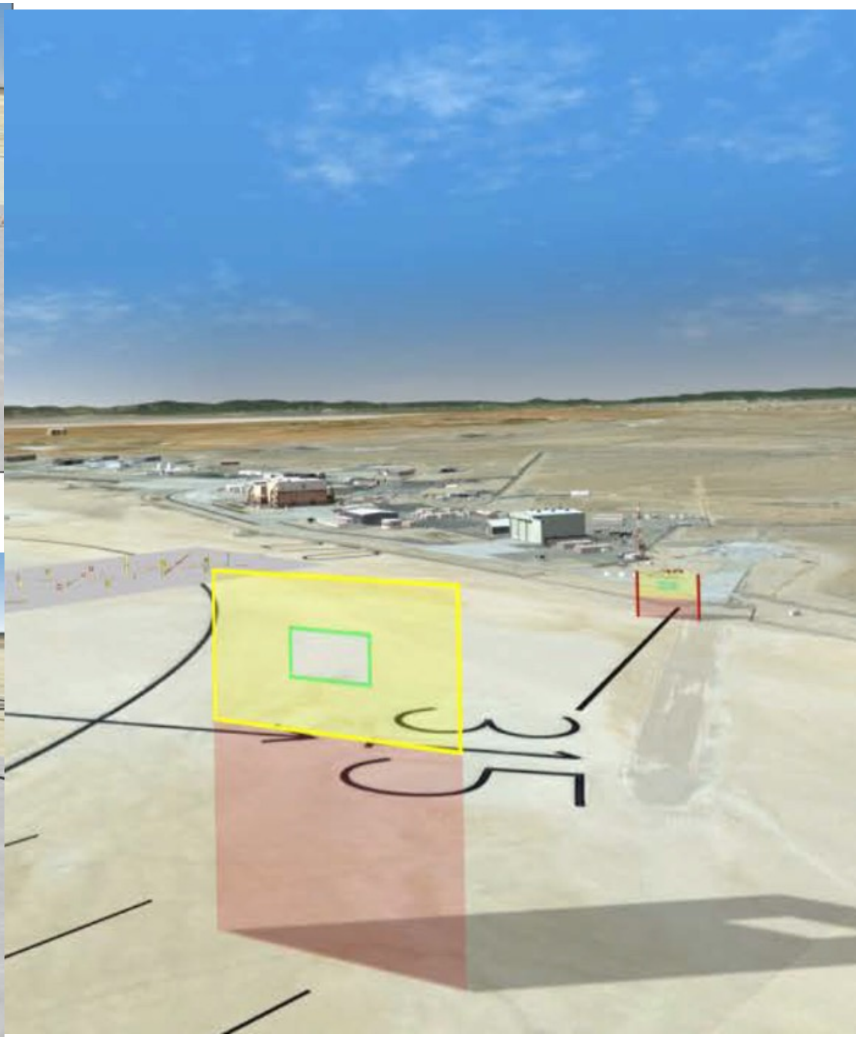
Precision Hover Course



Rejected Takeoff



Heliport Approach



Example Test Card

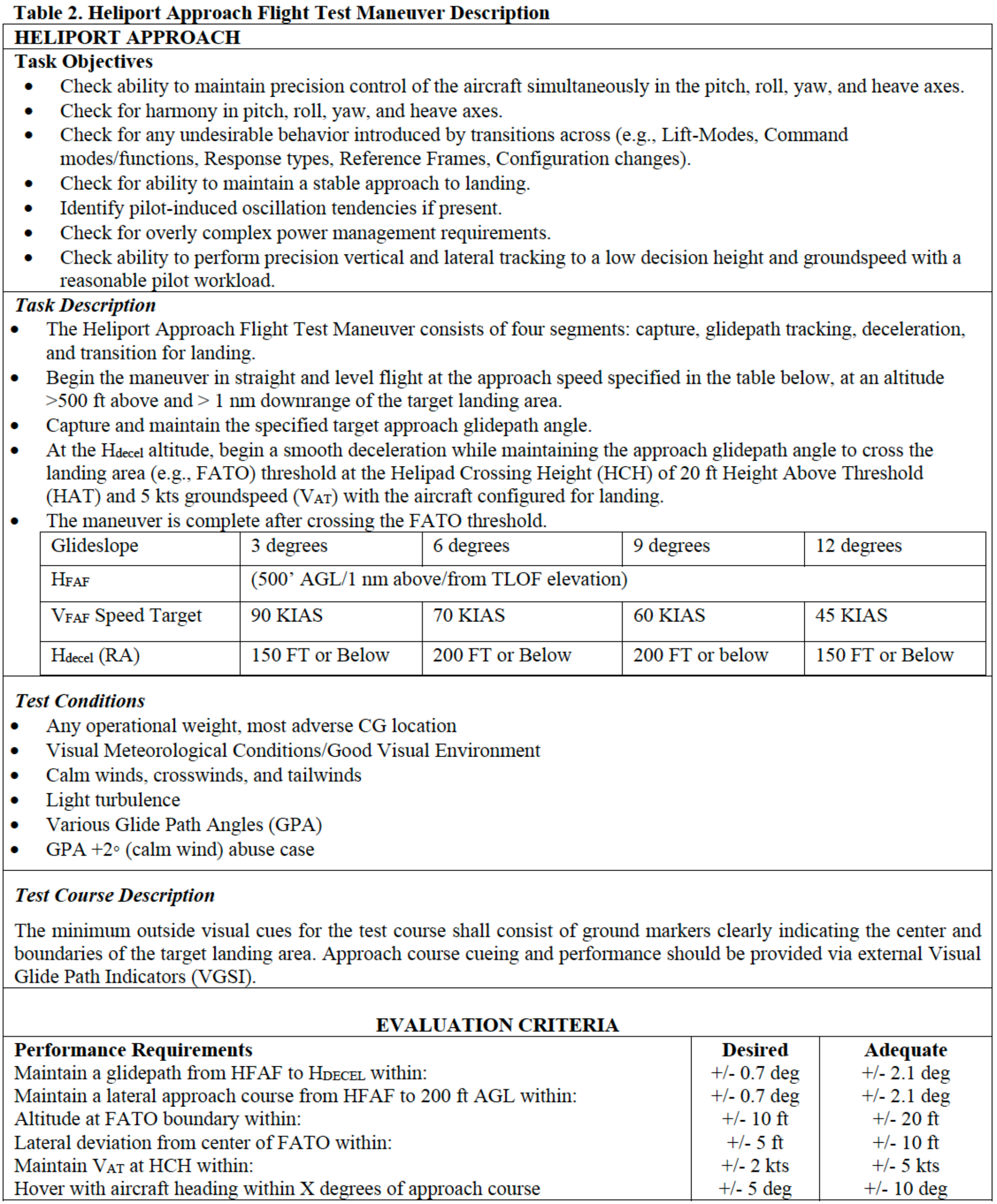


Table 2. Heliport Approach Flight Test Maneuver Description

HELIPORT APPROACH

Task Objectives

- Check ability to maintain precision control of the aircraft simultaneously in the pitch, roll, yaw, and heave axes.
- Check for harmony in pitch, roll, yaw, and heave axes.
- Check for any undesirable behavior introduced by transitions across (e.g., Lift-Modes, Command modes/functions, Response types, Reference Frames, Configuration changes).
- Check for ability to maintain a stable approach to landing.
- Identify pilot-induced oscillation tendencies if present.
- Check for overly complex power management requirements.
- Check ability to perform precision vertical and lateral tracking to a low decision height and groundspeed with a reasonable pilot workload.

Task Description

- The Heliport Approach Flight Test Maneuver consists of four segments: capture, glidepath tracking, deceleration, and transition for landing.
- Begin the maneuver in straight and level flight at the approach speed specified in the table below, at an altitude >500 ft above and > 1 nm downrange of the target landing area.
- Capture and maintain the specified target approach glidepath angle.
- At the H_{decel} altitude, begin a smooth deceleration while maintaining the approach glidepath angle to cross the landing area (e.g., FATO) threshold at the Helipad Crossing Height (HCH) of 20 ft Height Above Threshold (HAT) and 5 kts groundspeed (V_{AT}) with the aircraft configured for landing.
- The maneuver is complete after crossing the FATO threshold.

Glideslope	3 degrees	6 degrees	9 degrees	12 degrees
H_{FAF}	(500’ AGL/1 nm above/from TLOF elevation)			
V_{FAF} Speed Target	90 KIAS	70 KIAS	60 KIAS	45 KIAS
H_{decel} (RA)	150 FT or Below	200 FT or Below	200 FT or below	150 FT or Below

Test Conditions

- Any operational weight, most adverse CG location
- Visual Meteorological Conditions/Good Visual Environment
- Calm winds, crosswinds, and tailwinds
- Light turbulence
- Various Glide Path Angles (GPA)
- GPA +2° (calm wind) abuse case

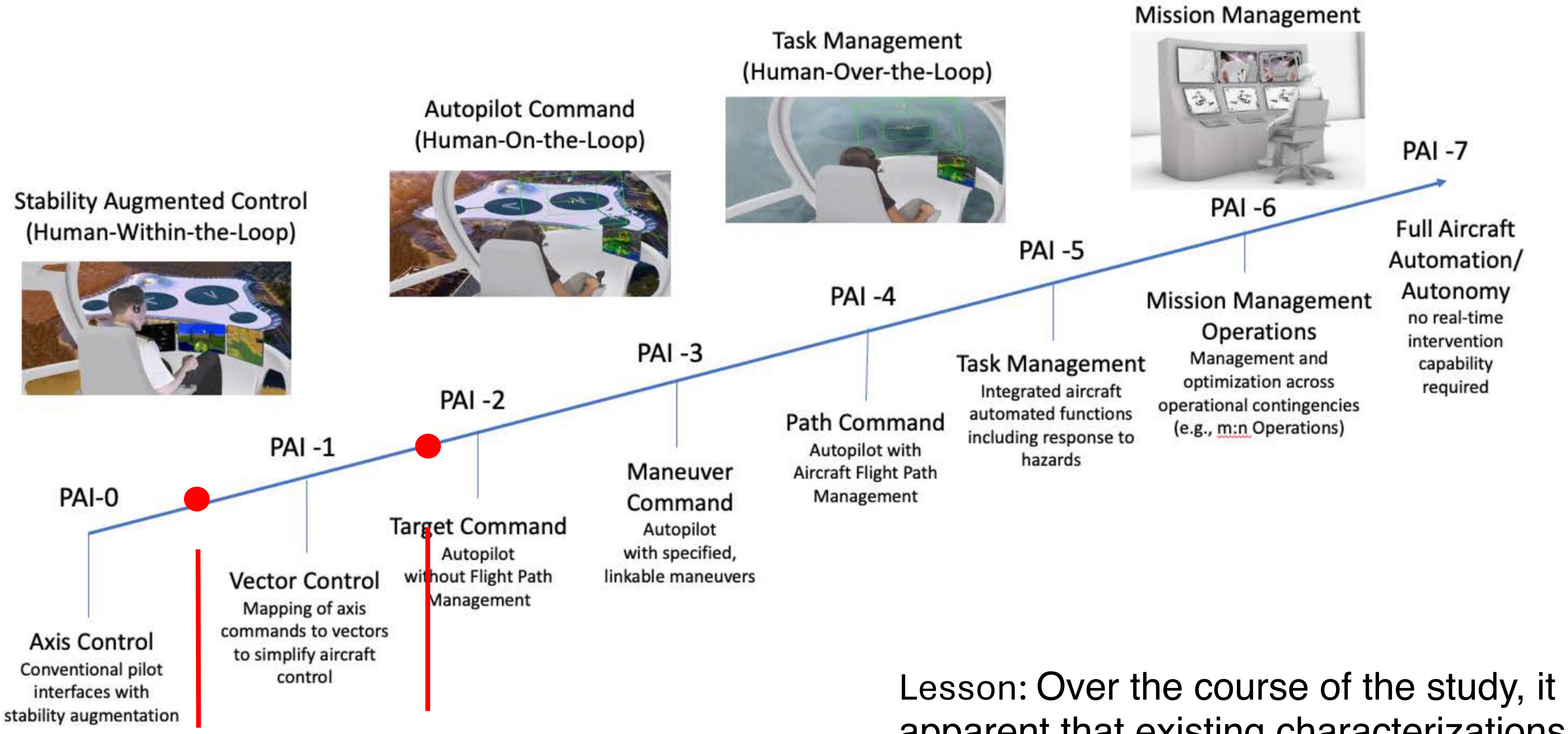
Test Course Description

The minimum outside visual cues for the test course shall consist of ground markers clearly indicating the center and boundaries of the target landing area. Approach course cueing and performance should be provided via external Visual Glide Path Indicators (VGSI).

EVALUATION CRITERIA

Performance Requirements	**Desired**	**Adequate**
Maintain a glidepath from HFAF to H_{DECEL} within:	+/- 0.7 deg	+/- 2.1 deg
Maintain a lateral approach course from HFAF to 200 ft AGL within:	+/- 0.7 deg	+/- 2.1 deg
Altitude at FATO boundary within:	+/- 10 ft	+/- 20 ft
Lateral deviation from center of FATO within:	+/- 5 ft	+/- 10 ft
Maintain V_{AT} at HCH within:	+/- 2 kts	+/- 5 kts
Hover with aircraft heading within X degrees of approach course	+/- 5 deg	+/- 10 deg

The Pilot-Automation-Interaction framework



Stability Augmented Control (Human-Within-the-Loop)

Autopilot Command (Human-On-the-Loop)

Task Management (Human-Over-the-Loop)

Mission Management

PAI-0

Axis Control
Conventional pilot interfaces with stability augmentation

PAI -1

Vector Control
Mapping of axis commands to vectors to simplify aircraft control

PAI -2

Target Command
Autopilot without Flight Path Management

PAI -3

Maneuver Command
Autopilot with specified, linkable maneuvers

PAI -4

Path Command
Autopilot with Aircraft Flight Path Management

PAI -5

Task Management
Integrated aircraft automated functions including response to hazards

PAI -6

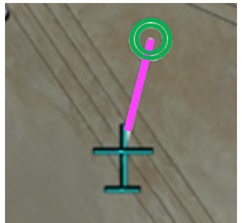
Mission Management Operations
Management and optimization across operational contingencies (e.g., m:n Operations)

PAI -7

Full Aircraft Automation/ Autonomy
no real-time intervention capability required

CC–1, CC-2 Hover Vector

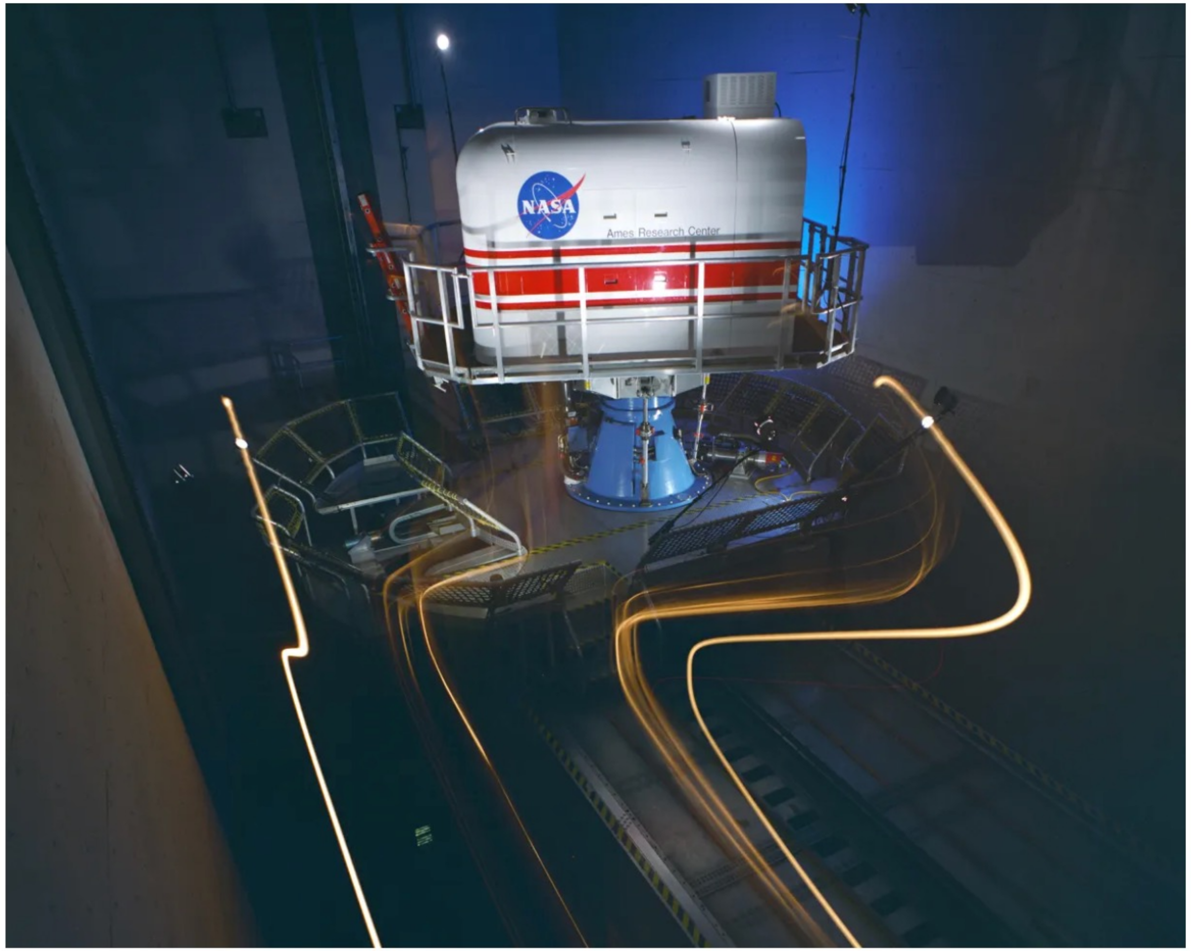
CC -3
Hover Target Command



Lesson: Over the course of the study, it became apparent that existing characterizations of Human-Automation Interaction were not sufficient to describe the different aircraft automation configurations to the extent needed.

AEP-1 Vertical Motion Simulator – Cab mounted on beam

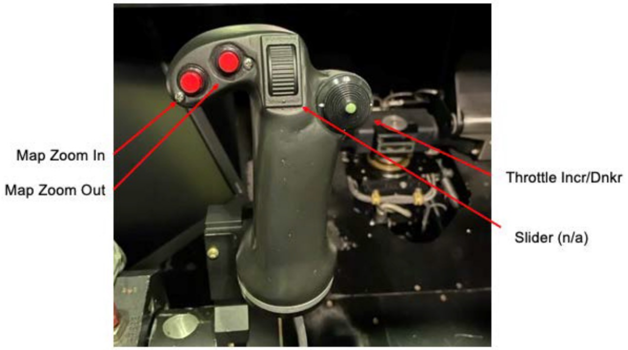
Vertical
Motion
Simulator
Cab



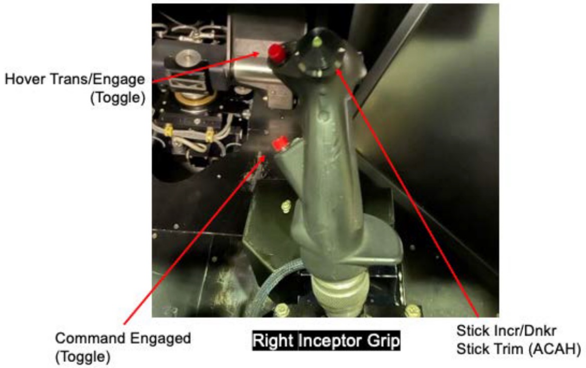
The Vertical Motion Simulator plays a vital role in the advancement of aerospace vehicle design, development, and training.

NASA / Dominic Hart

AEP-1 Inside VMS Cab

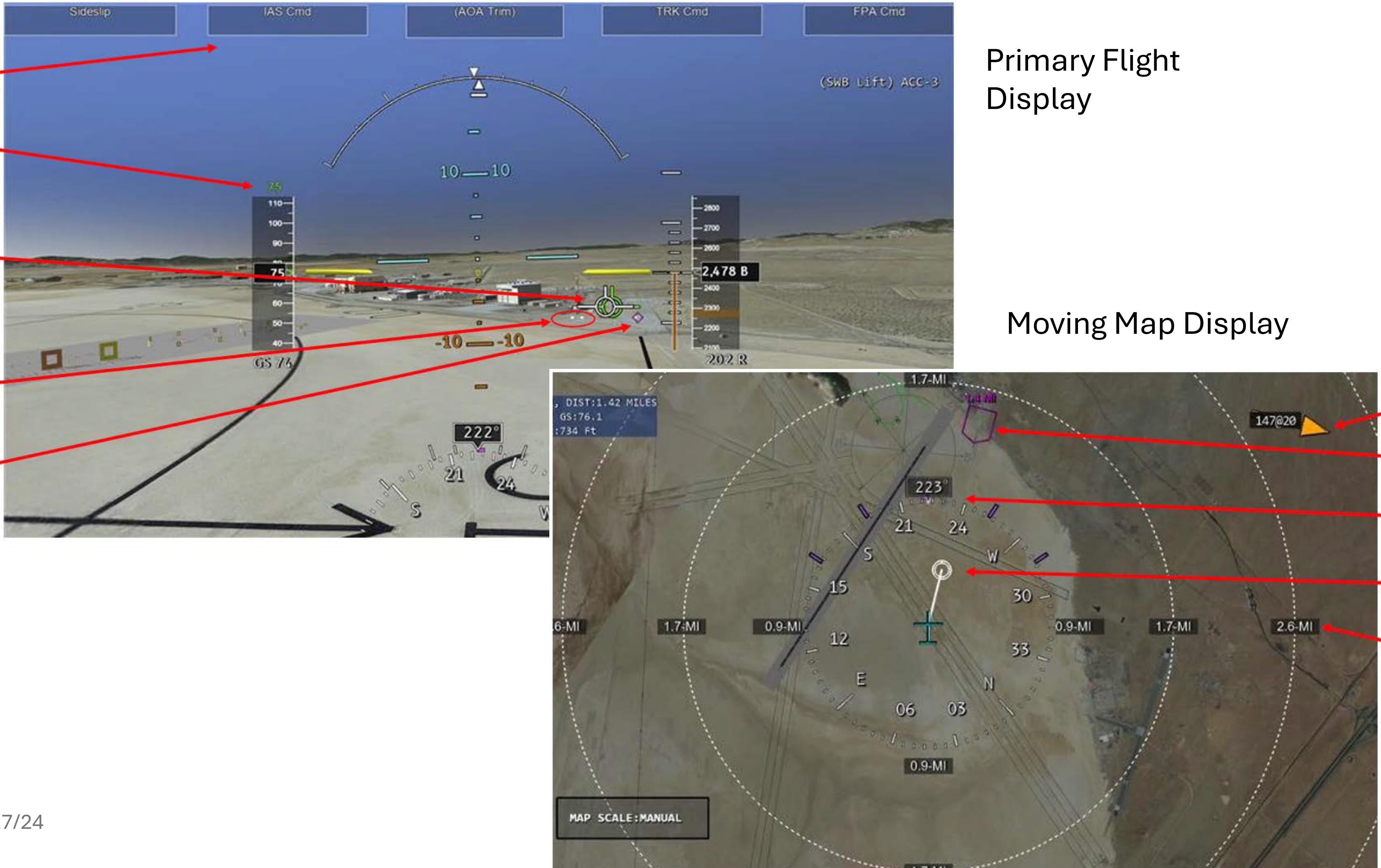


Left Inceptor Grip



Right Inceptor Grip

AEP-1 VMS Cab Displays



Primary Flight Display

Moving Map Display

Flight Mode Annunciators

Speed Targets CC-3 only

Flight Path Guidance (white) and Target (green)(CC-3 only)

PAPI Approach lights

Landing Site waypoint (Future Automation feature)

Wind Cue

Destination Cue (Future automation feature)

Compass Rose

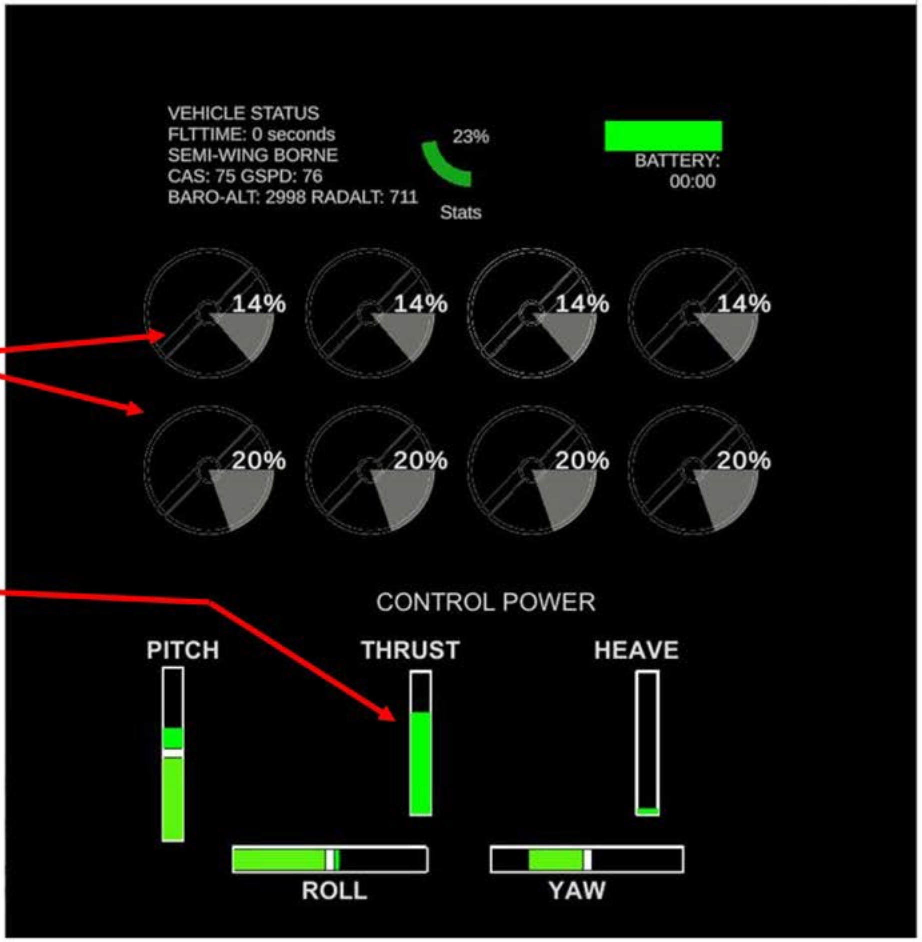
Decelerate to Hover Predictor

Range Rings

3/27/24

AEP-1 Engine Health and Engineering Displays

Engine Health Display



VEHICLE STATUS
FLTTIME: 0 seconds
SEMI-WING BORNE
CAS: 75 GSPD: 76
BARO-ALT: 2998 RADALT: 711

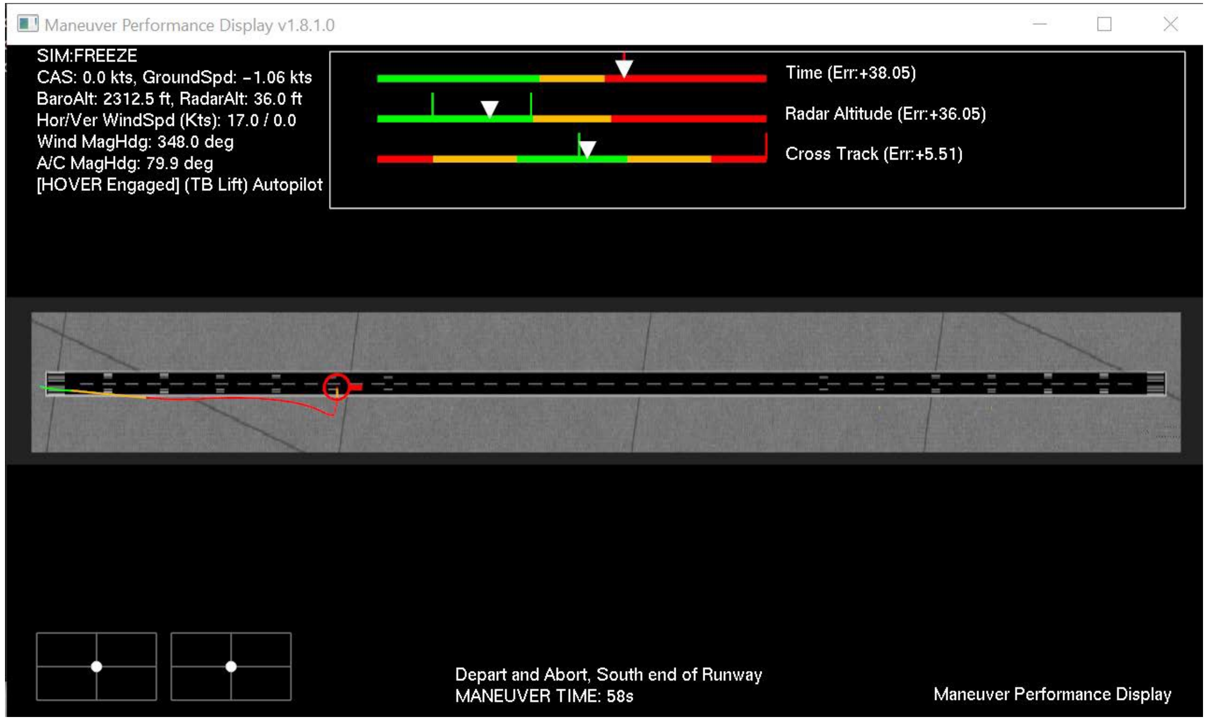
BATTERY:
00:00

Percent RPM for each thruster (0-100)

Thrust from propeller

Pitch, heave, roll, and yaw are effector limits; Control is saturated when bar is fully green.

Engineering Display (Observers Seat)



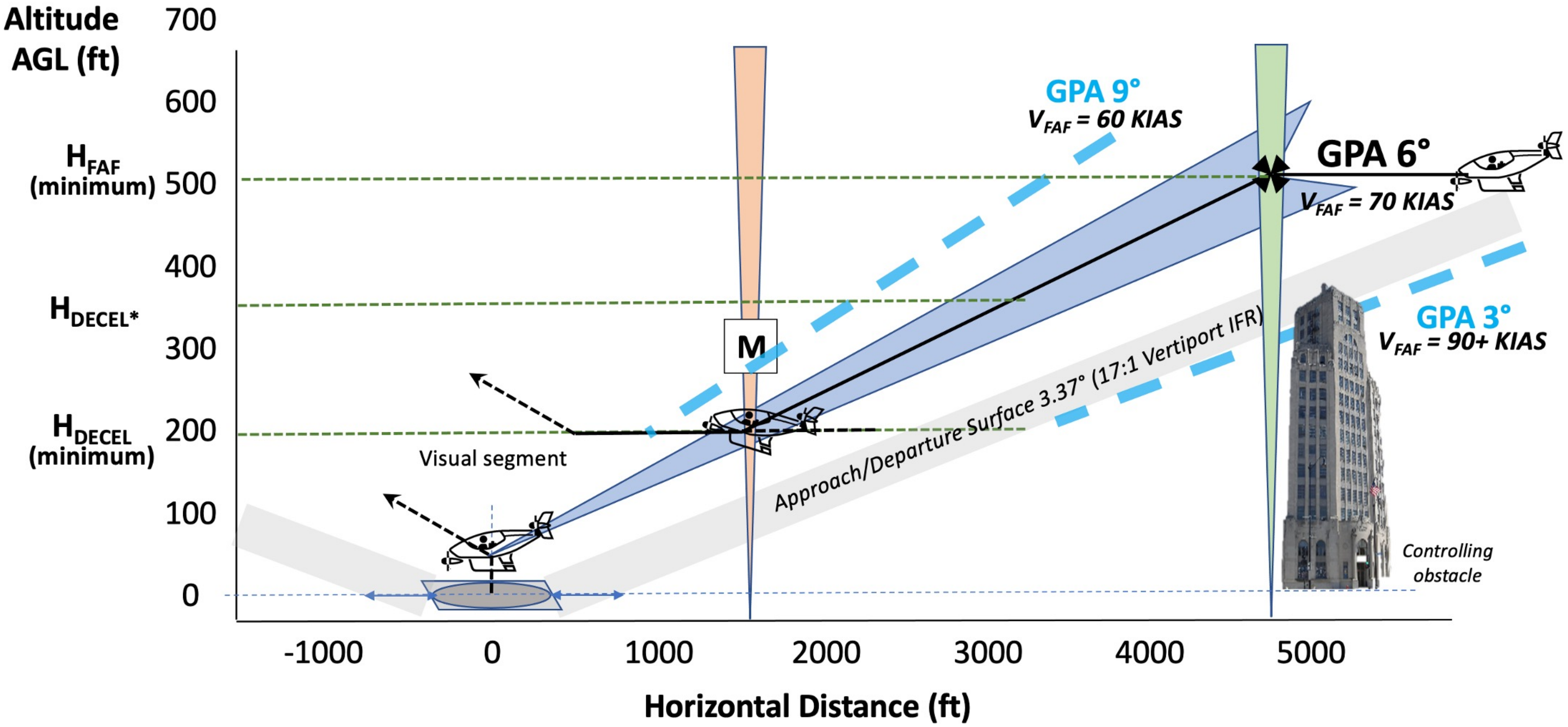
Maneuver Performance Display v1.8.1.0

SIM:FREEZE
CAS: 0.0 kts, GroundSpd: –1.06 kts
BaroAlt: 2312.5 ft, RadarAlt: 36.0 ft
Hor/Ver WindSpd (Kts): 17.0 / 0.0
Wind MagHdg: 348.0 deg
A/C MagHdg: 79.9 deg
[HOVER Engaged] (TB Lift) Autopilot

Time (Err:+38.05)
Radar Altitude (Err:+36.05)
Cross Track (Err:+5.51)

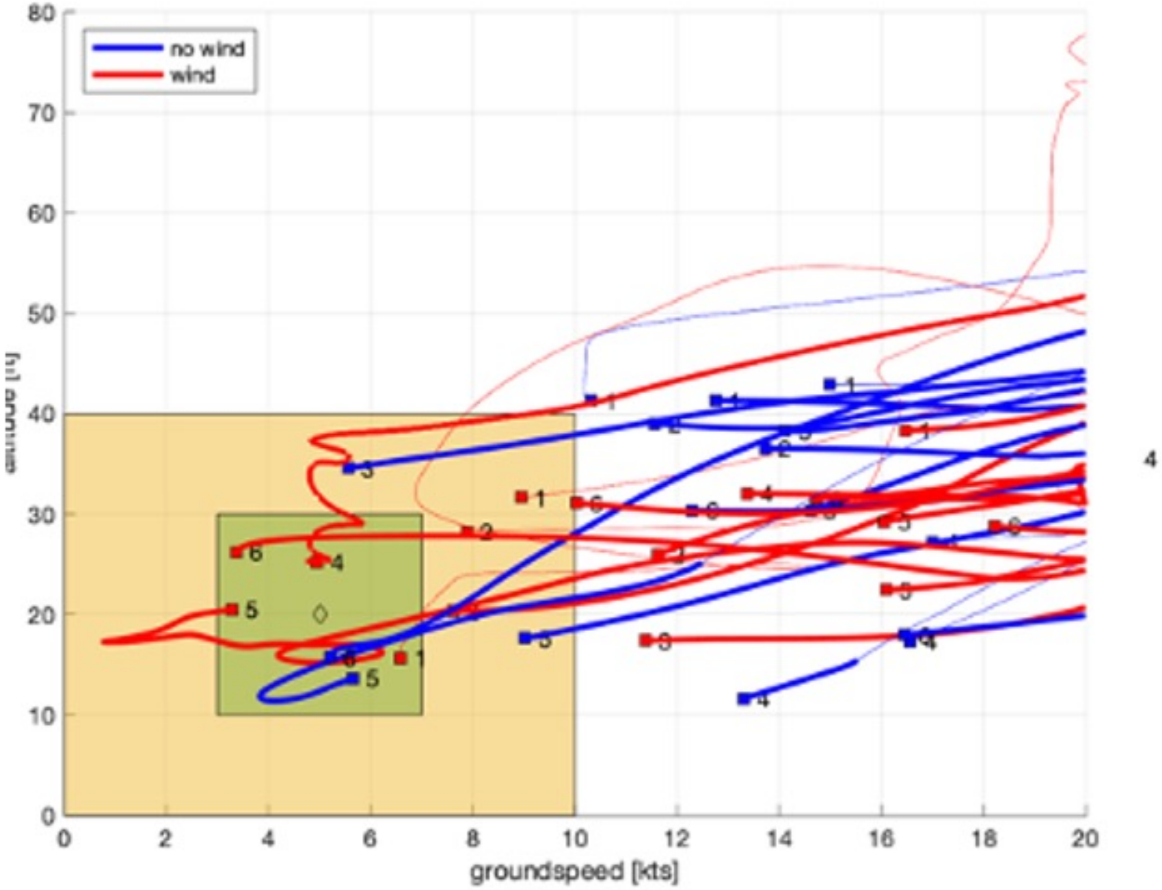
Depart and Abort, South end of Runway
MANEUVER TIME: 58s

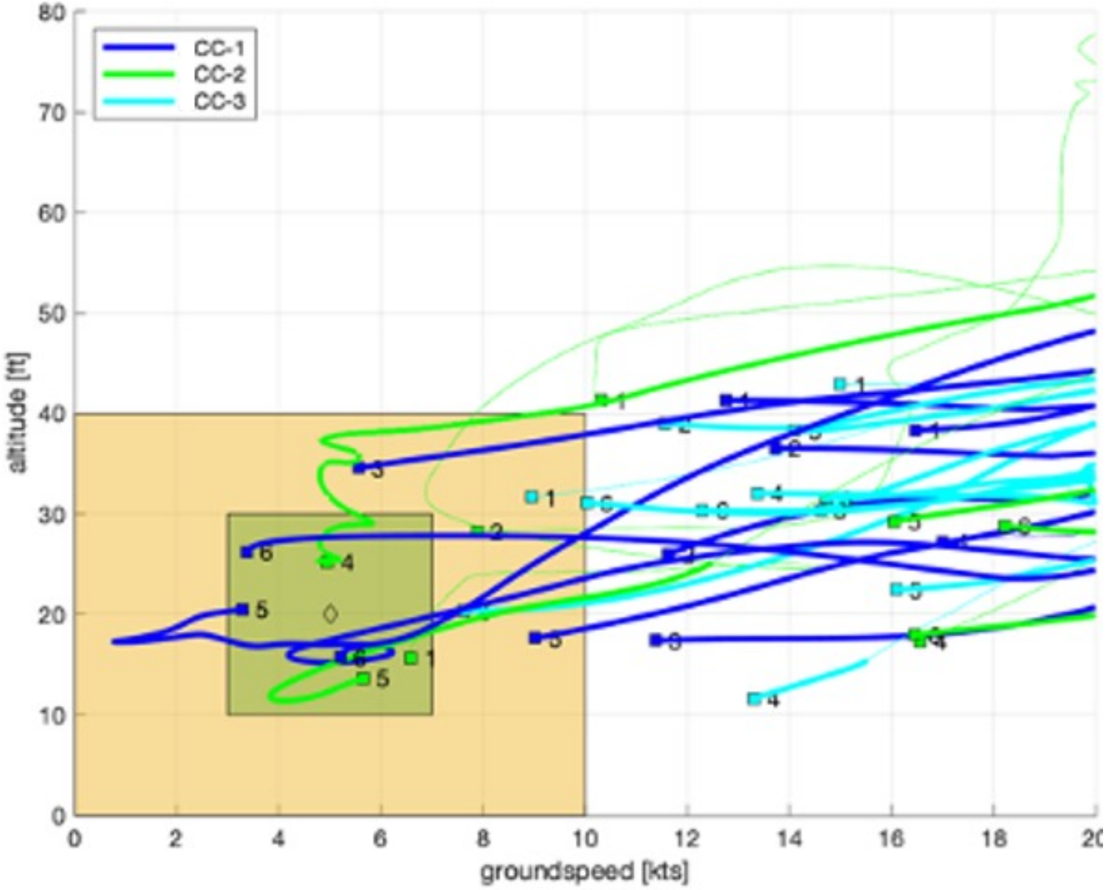
AEP-1 Approach Procedure



Heliport Approach

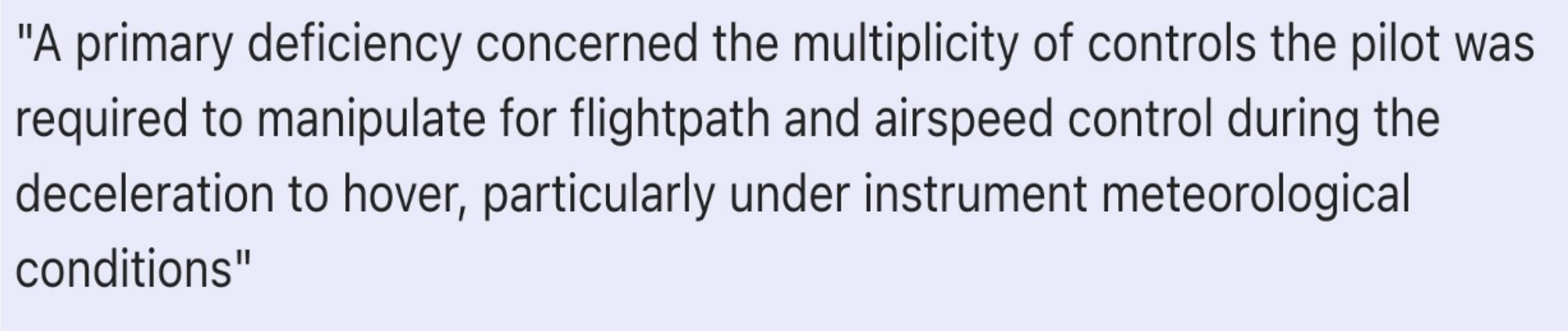
AEP -1 Heliport Approach Results





Reflection on Interesting Remarks From VTOL History

Bell XV-3 (experimental tilt rotor)



"A primary deficiency concerned the multiplicity of controls the pilot was required to manipulate for flightpath and airspeed control during the deceleration to hover, particularly under instrument meteorological conditions"

AEP-1 Summary and Lessons 1

- Industry representative aircraft, interface and automation concepts
  - See Kaneshige et al. 2023 for Flight Technical Performance

- “Flyable but not certifiable”
  - Many task – inceptor combinations were not certifiable as implemented

- Precision Hover
  - CC-3 (highest automation condition) “Not possible to meet the performance criteria without using the display…”

- Rejected Takeoff
  - Automation could not keep up in the wind condition as the aircraft had marginal controllability and the automation could into predict the wind effects
  - Some pilots flying manually could reach desired performance

- Heliport Approach
  - “ couldn’t predict the behavior of the aircraft…”
  - “had to learn to get out of the way of the automation…”
  - Bird on the wire approach

AEP-1 Summary and Lessons 2

General observations:

- Split between Acelab training and VMS evaluations worked very well, thanks to the good team and great coordination between everyone! 😊
- The 3 scenarios considered in this study (precision hover, heliport approach, rejected takeoff) were effective in highlighting strengths and weaknesses between different control strategies with different levels of automation. There is no silver bullet in the ACC’s, they all have their pro’s and cons.
- Windy conditions made the scenarios completely different compared to the no wind conditions. Mode transitions or inceptor mapping transitions are always a high risk moment when some (cross) wind is involved.
- The difference between single switch in acelab versus double switch in VMS for hover enable/disable was confusing and affected every pilot’s performance at some point.
- Cooper harper: coupling between performance and workload becomes less correlated for higher automation levels.

AEP-1 Summary and Lessons. 3

- **Some observations specific for certain scenarios:**
  - Precision hover:
    - Furniture / cues insufficient for longitudinal requirements, some needed more coaching on map use and zooming in so that they reached desired performance.
    - ACC-3: longitudinal overshoot was major point of fixation.
  - Approach:
    - Split up between GS intercept and hold on one hand and decel phase on the other hand. Heading requirement is only relevant above FATO, decrab maneuver.
    - Decel phase was challenging. Similar to shuttle flare?
    - GS / LOC deviations during deceleration are not as important anymore as before deceleration, since it becomes a visual task (input from Dave Webber). How do we deal with this?
    - HQTE display not helpful for FATO criteria, we need additional information about FATO transition.
    - Recommendation to spread decel a bit more out

AEP-1 Summary and Lessons 4

- **Rejected takeoff:**
  - Very challenging in wind! Keep sideslip / crab under control
  - Two very different approaches: early compensation (needed time to develop this) vs let it go. Pilot workload vs passenger comfort (analysis required).
  - Mode changes resulted in disturbances or PIO's with stick deflections -> very upsetting and unacceptable, especially ACC-2.

Some other observations:

- Negative habit transfer in terms of inceptors, and attitude to vector, was a huge thing, as expected

- Wide variations: pilots deep in the loop, wanted to pitch but couldn't. Mostly industry guys made transition to flying flight path vector instead of attitude fairly quickly (because that is what they are doing).

- Increase in automation ACC-3: have to get out of its way, pilot trying to help actually hurts. Automation should allow the pilot to 'help' the system. Liked to 'set and forget'.

AEP-1 Summary and Lessons 5

Some other observations continued:

- Display control interaction, ACC-3 not practically doable in hover without map view.
- ACC-3: ability to initially set up accurately and then ‘forget’. Few quirks in hover and localizer.
- Experienced pilots showed that there is no silver bullet ACC mode, they all have pro’s and cons.
- Precision hover was more homogenous, approach: activating hover mode sooner or later,
- Different problems arose either by going fast or slow through mode changes
- Pilots were most enthusiastic about the rejected takeoff
- 3 helicopter pilots, others not much rotary. 2 DER pilots, 2 government, 2 from companies. Industry guys much more comfortable with higher automation strategies. Different strategies with different control concepts.
- We looked at experienced participants only! It could be interesting to see how ‘novice’ and only minimally trained or inexperienced pilots would perform. No negative habit transfer, but maybe other issues?

Thank You

Loran.a.Haworth@nasa.gov
michael.s.feary@nasa.gov
john.t.kaneshige@nasa.gov
thomas.lombaerts@nasa.gov

STOP

STOP

End Of Slides

EXTRA SLIDES AND INFORMATION

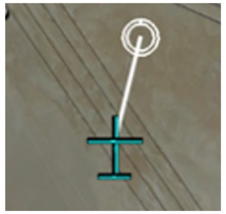
EXTRA BACKUP SLIDES AND INFORMATION FOLLOW

Hover Button

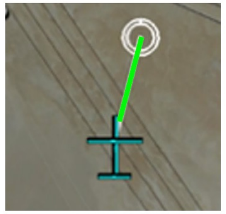
- **Automation Condition 1** (g_svo.ipr = 1)
  - Hover Button arms Hover mode
  - Hover mode engages below 10 KFGS
- **Automation Condition 2** (g_svo.ipr = 2)
  - Hover Button engages Transition to Hover
    - Automatically commands a 2.5 knot/sec deceleration rate[1]
    - Automatically commands a decrab maneuver[2]
    - Right stick response transitions to command a vector-based FPA and track angle target
  - Hover Mode engages below 10 KFGS
- **Automation Condition 3** (g_svo.ipr = 3)
  - Hover Button engaged Transition to a Hover Point
    - Automatically latches to helipad if “close enough” when transition is engaged
    - Automatically commands a deceleration to the hover point[1]
    - Automatically commands a decrab maneuver[2]
    - Right stick response transitions to command a vector-based FPA target[2] and the computed track angle to the hover point[3]
  - Hover Point Mode engages upon hover point capture

1. Can be modified with left inceptor inputs
2. Can be modified with right inceptor twist inputs
3. Can be modified with right inceptor lateral inputs


Flight Path Vector


Predicted Hover Point Along Current Track


Commanded Flight Path Vector


Predicted Hover Point Along Commanded Track


Commanded/Computed Flight Path Vector


Commanded Hover Point Along Computed Track

Inceptor Command Response

Lifting Modes *f*(KIAS)	**Left Stick**	**Right Stick**			**Groundspeed**
	Speed *Accelerate* *Decelerate*	**Vertical** *Descend* *Climb*	**Lateral** *Go Left* *Go Right*	**Directional** *Yaw Left* *Yaw Right*	
Hover Mode	Forward Groundspeed	Vertical Speed	Lateral Groundspeed	Heading Rate	**(0-20 KGS)**
TB Lift (0-20 KIAS)	Acceleration[1]	Vertical Acceleration	Bank Angle	Heading Rate	**(0-34 KGS)**
STB Lift (15-40 KIAS)		FPA Rate	Roll Rate	Crab Angle	**(34+ KGS)**
SWB Lift (30-100 KIAS)	Acceleration[2]			Sideslip Angle	
WB Lift (90-120 KIAS)					

1. Acceleration is relative to forward groundspeed
2. Acceleration is relative to indicated airspeed

Transition to Hover Command Response

Lifting Modes *f*(KIAS)	Left Stick	Right Stick			Groundspeed
	Speed *Accelerate* *Decelerate*	Vertical *Descend* *Climb*	Lateral *Go Left* *Go Right*	Directional *Yaw Left* *Yaw Right*	
Hover Engaged	Forward Groundspeed	Vertical Speed	Lateral Groundspeed	Heading Rate	**(0-20 KGS)**
TB Lift (0-20 KIAS)	Deceleration[1] (2.5 knot/sec)	Vertical Acceleration	Lateral Acceleration	Heading Rate	**(0-34 KGS)**
STB Lift (15-40 KIAS)		FPA Rate	Track Rate		**(34+ KGS)**
SWB Lift (30-100 KIAS)	Deceleration[2] (2.5 knot/sec)			Crab Angle (de-crab maneuver)	
WB Lift (90-120 KIAS)					

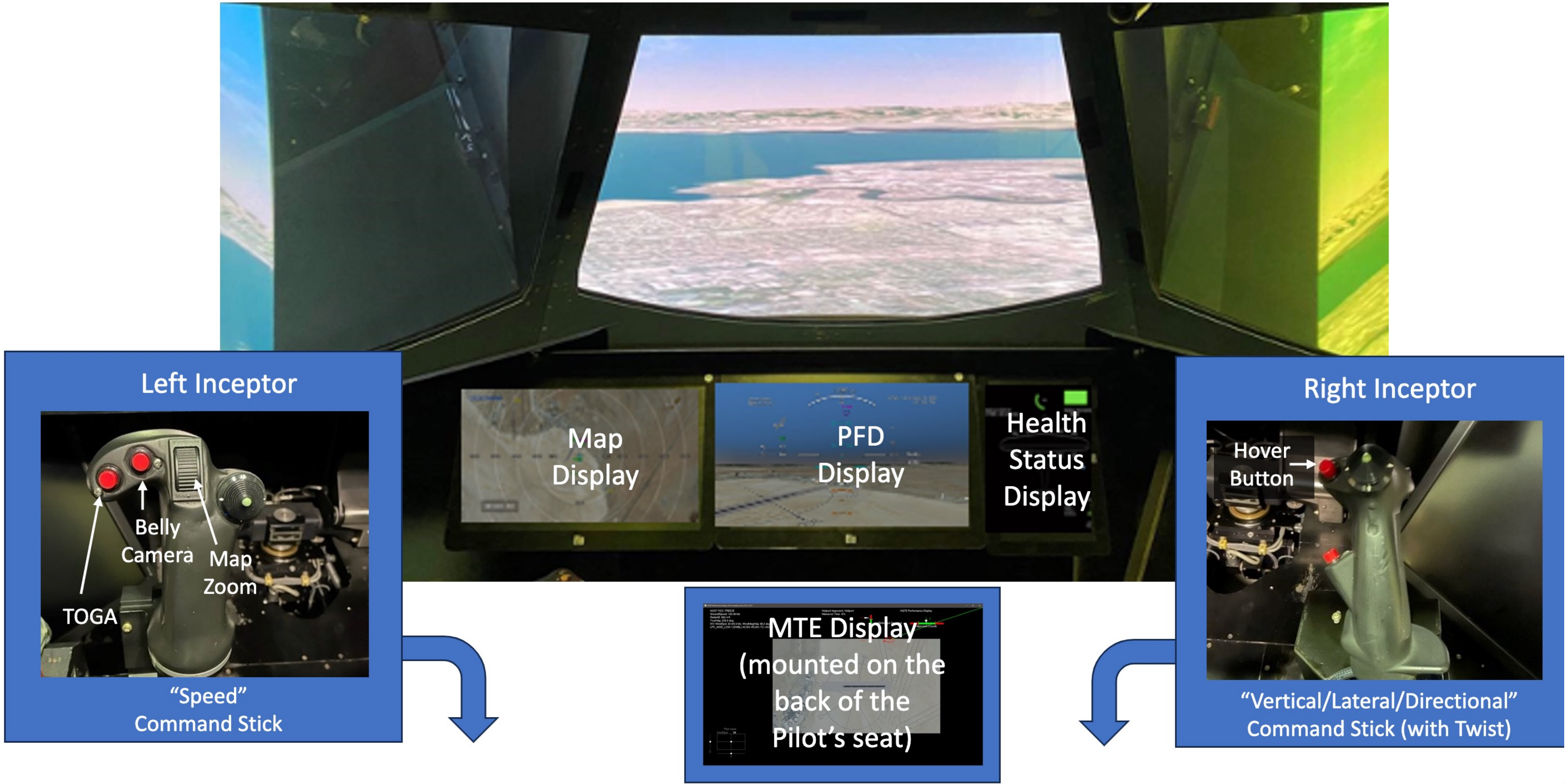
1. Deceleration is relative to forward groundspeed
2. Deceleration is relative to indicated airspeed

Transition to Hover Point Command Response

	Left Stick	Right Stick			
Lifting Modes *f*(KIAS)	**Speed** *Accelerate*  *Decelerate*	**Vertical** *Descend*  *Climb*	**Lateral** *Go Left*  *Go Right*	**Directional**  *Yaw Left* *Yaw Right*	**Groundspeed**
Hover Engaged	Moves Hover Point Longitudinally[1]	Vertical Speed	Moves Hover Point Laterally[2]	Heading Rate	(0-20 KGS)
TB Lift **(0-20 KIAS)**		Vertical Acceleration		Heading Rate	(0-34 KGS)
STB Lift **(15-40 KIAS)**		FPA Rate			(34+ KGS)
SWB Lift **(30-100 KIAS)**				Crab Angle (de-crab maneuver)	
WB Lift **(90-120 KIAS)**					

1. Hover point moves forward/backward (relative to aircraft heading) at a rate which is a function of groundspeed
2. Hover point moves sideways (relative to aircraft heading) at a rate which is a function of distance (to the hover point)

R-Cab Layout


Left Inceptor
Belly Camera
Map Zoom
TOGA
“Speed” Command Stick
Map Display
PFD Display
Health Status Display
MTE Display (mounted on the back of the Pilot’s seat)
Right Inceptor
Hover Button
“Vertical/Lateral/Directional” Command Stick (with Twist)

eVTOL Operational Dimensions

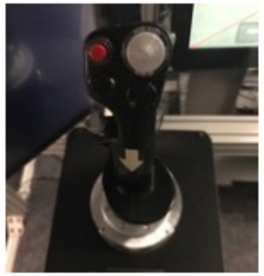
Aircraft Performance

Pilot Requirements

Operations

Automated Systems

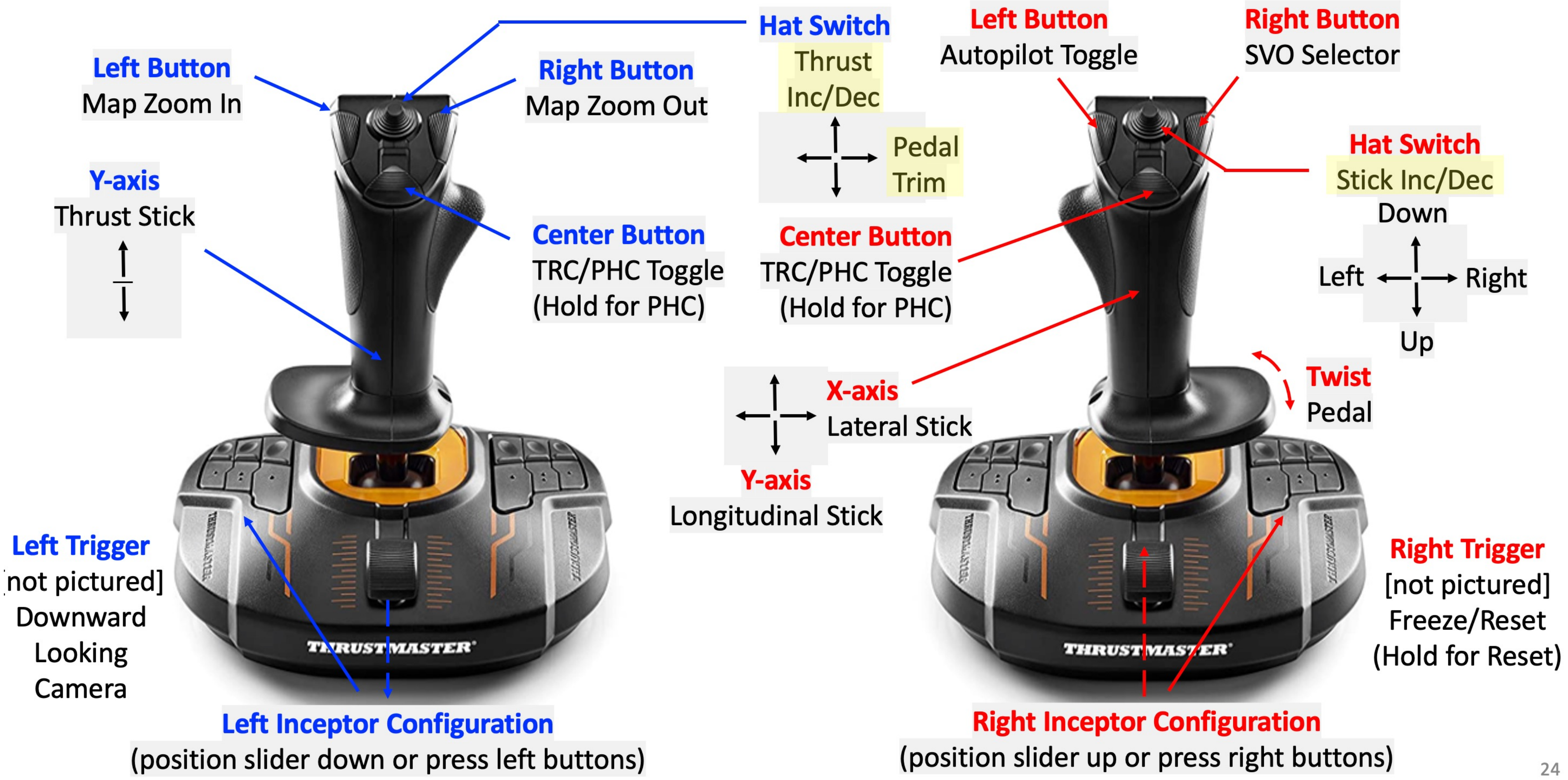
Controls



Displays

Thrustmaster T16000 Dual Inceptors (Remote Capability)

(Rudder pedals not shown in slide)



Left Button
Map Zoom In

Right Button
Map Zoom Out

Y-axis
Thrust Stick

Center Button
TRC/PHC Toggle
(Hold for PHC)

Left Trigger
[not pictured]
Downward
Looking
Camera

Left Inceptor Configuration
(position slider down or press left buttons)

Hat Switch
Thrust
Inc/Dec
Pedal
Trim

Center Button
TRC/PHC Toggle
(Hold for PHC)

X-axis
Lateral Stick

Y-axis
Longitudinal Stick

Left Button
Autopilot Toggle

Right Button
SVO Selector

Hat Switch
Stick Inc/Dec
Down
Left
Right
Up

Twist
Pedal

Right Trigger
[not pictured]
Freeze/Reset
(Hold for Reset)

Right Inceptor Configuration
(position slider up or press right buttons)

Used in conjunction with Mac Computers

Advancing Electric Propulsion Aircraft Evaluation for Urban Air Mobility: Insights from NASA-Ames

This presentation delves into a recent evaluation conducted at NASA-Ames on the Vertical Motion Simulator, focusing on the handling qualities of Distributed Electric Propulsion VTOL (eVTOL) aircraft, specifically tailored for Urban Air Mobility (UAM) applications.

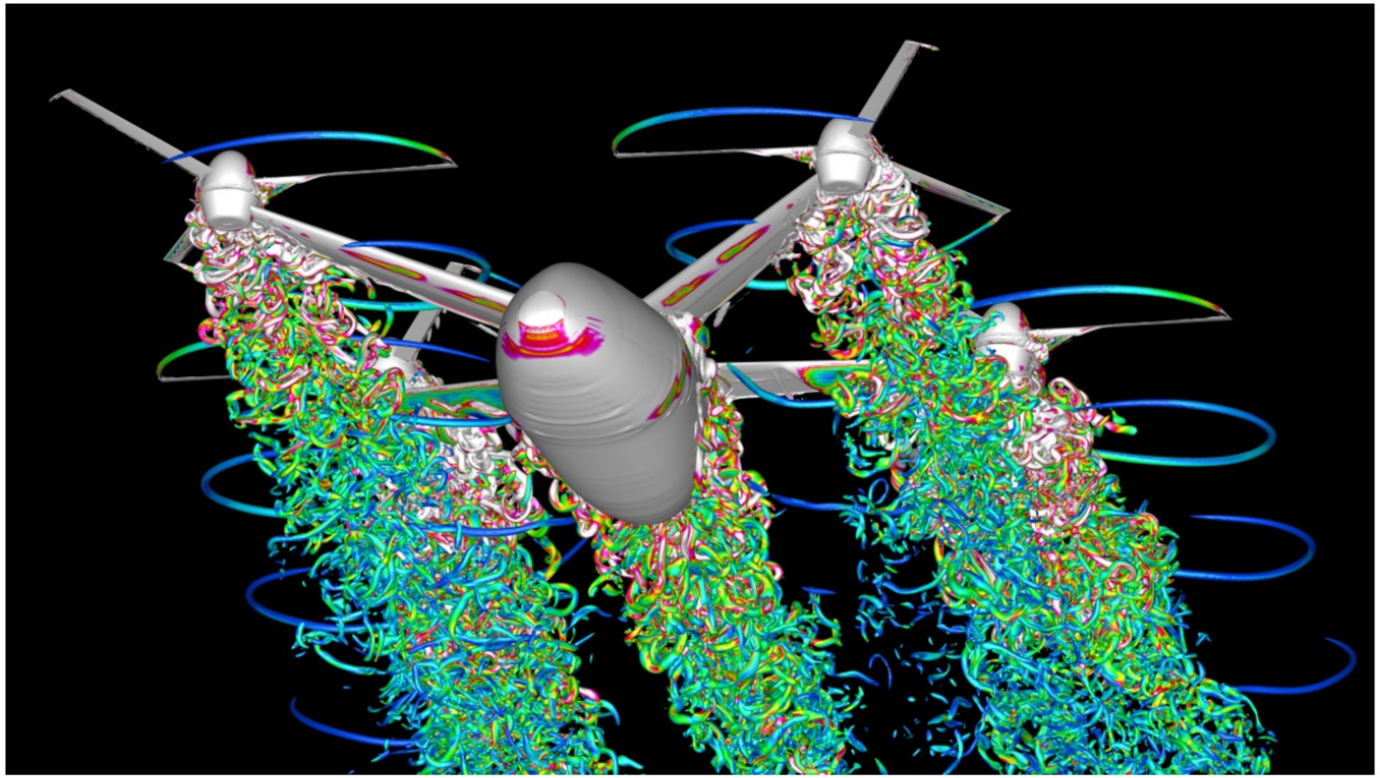
The presentation will focus on the recent effort to adapt and refine use of the Aeronautical Design Standard -33 (ADS-33) rotorcraft handling qualities developed by the U.S. Army and NASA to meet the diverse needs of civilian (eVTOL) concept evaluation.

A brief discussion of the author's personal test pilot insights in the early development of military Fly-By-Wire evaluation methods will also be provided.

The emergence of innovative eVTOL designs with unique lift capabilities and flight control systems, present both opportunities and challenges, particularly in ensuring safety amidst technological complexity.

To navigate these challenges, our investigation examined evaluation criteria designed to accommodate the varied configurations and advanced automation systems inherent in modern eVTOL aircraft.

Facilities

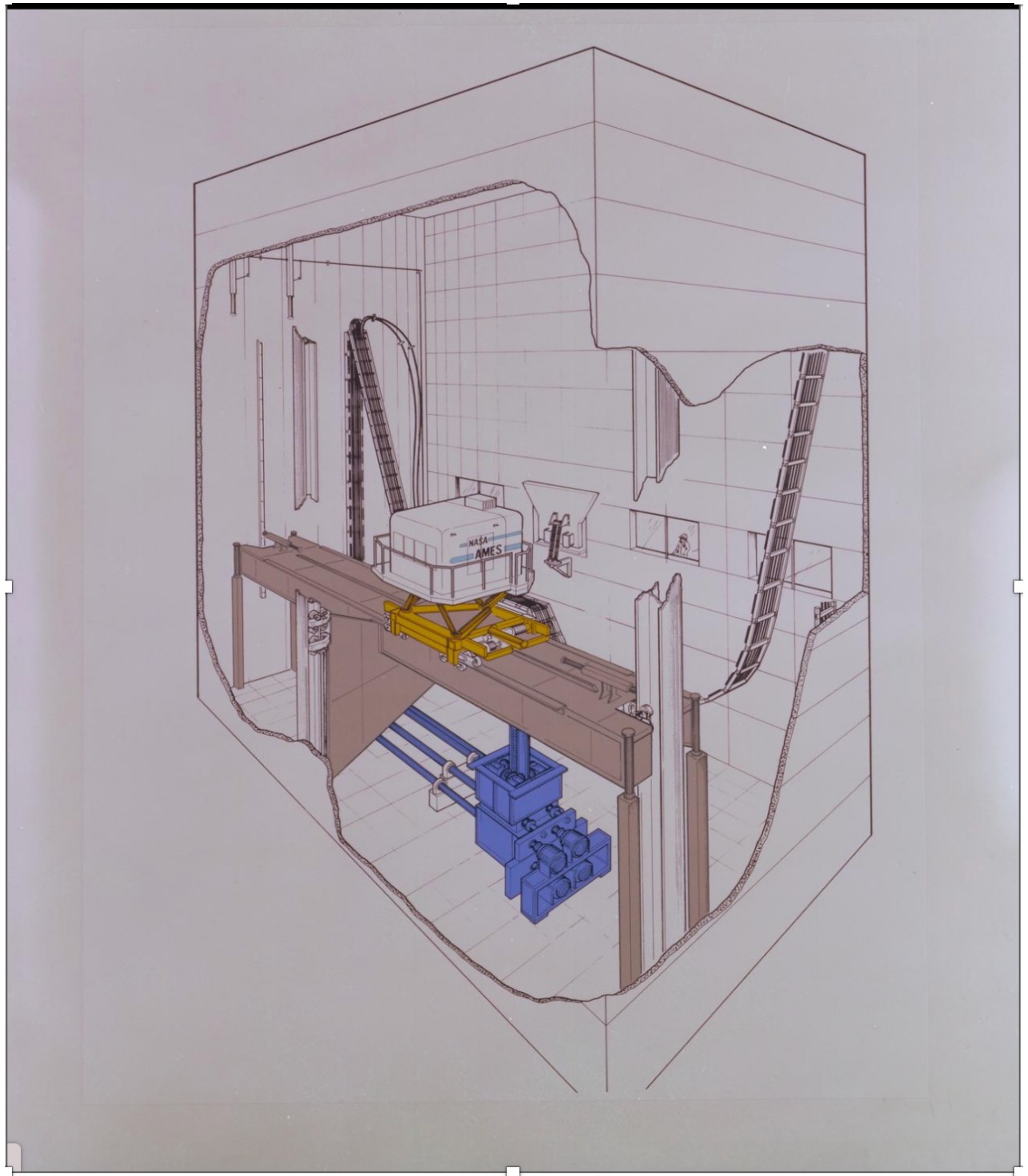


Two of Ames' longtime strengths – supercomputing and computational fluid dynamics – come together in this visualization of the flow of NASA's six-passenger quadcopter concept for Advanced Air Mobility.

NASA / Patricia Ventura Diaz

Facilities: NASA-Ames 80 X 120 Wind Tunnel

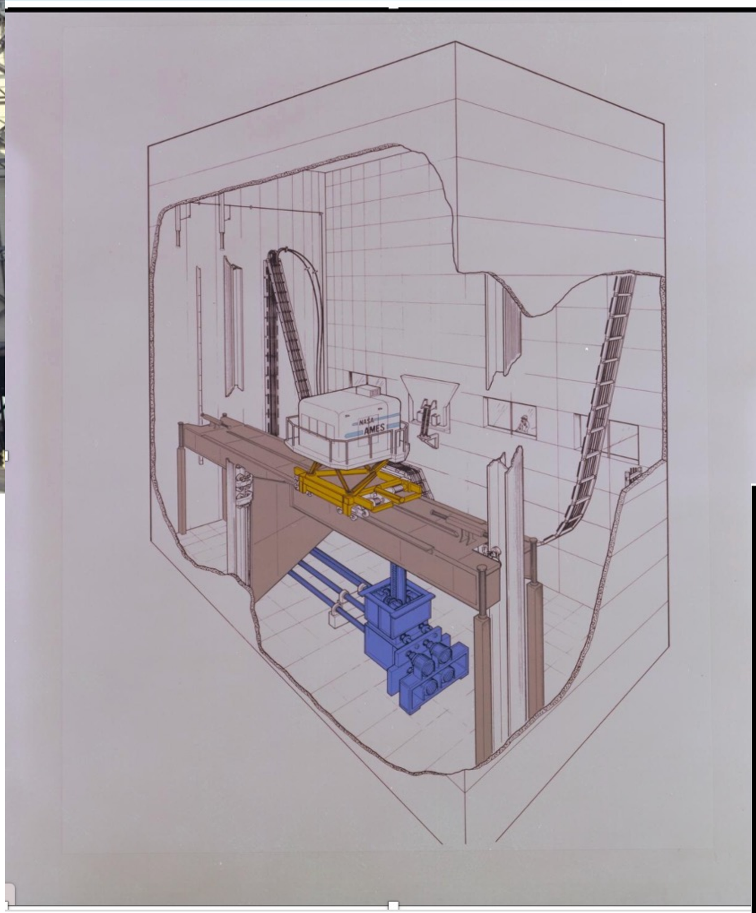
Facilities: Vertical Motion Simulator



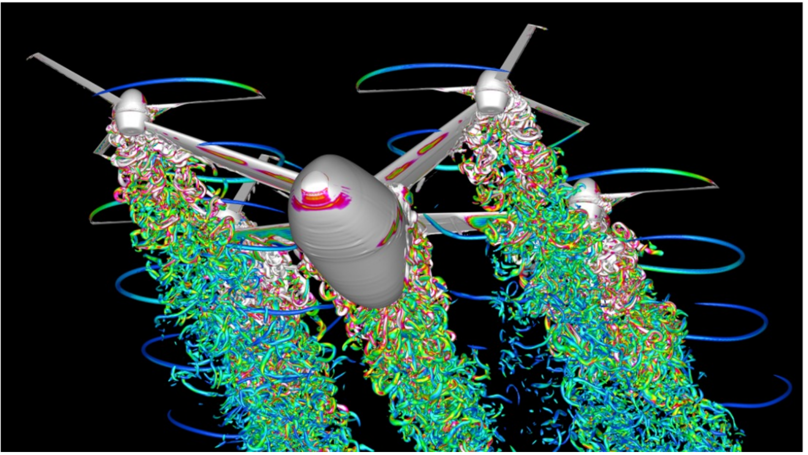
Introduction: Ames Facilities

80 X 120 Wind Tunnel

Vertical Motion Simulator (VMS)



Supercomputing & Computational Fluid Dynamics



ASCAL on the flight ramp, NASA A

NASA-Ames Vertical Flight Research

Introduction: Ames History: Early NASA-Ames/Army Vertical Flight Research

Ryan VZ-3RY Vertiplane

Bell X-14B (VTOL experimental aircraft)

Ryan XV-5B ("fan-in-wing")

Harrier AV-8B

AEP-1