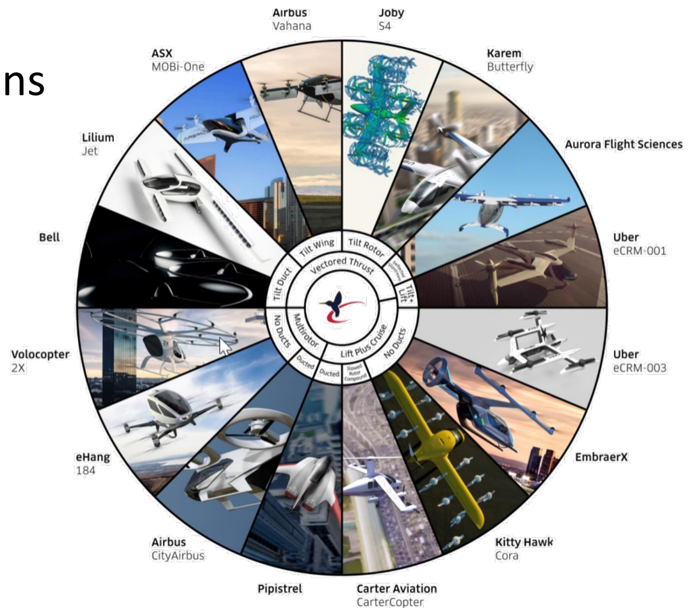
NASA Automation Enabled Pilot (AEP)
AEP -1 Study
Michael Feary

NASA – FAA Study Collaboration Roadmap

Evaluation of Aircraft Configurations



FAA VTOL Interface Design Study-1

June 2021

Feb. 2022

NASA Automation Enabled Pilot Study -1

FAA VTOL Interface Design Study-2

June 2022

FAA VTOL Interface Design Study – 3?

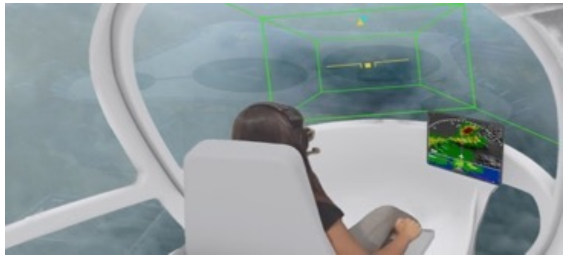
Spring 2023?

Spring 2024

NASA Automation Enabled Pilot Study - 2

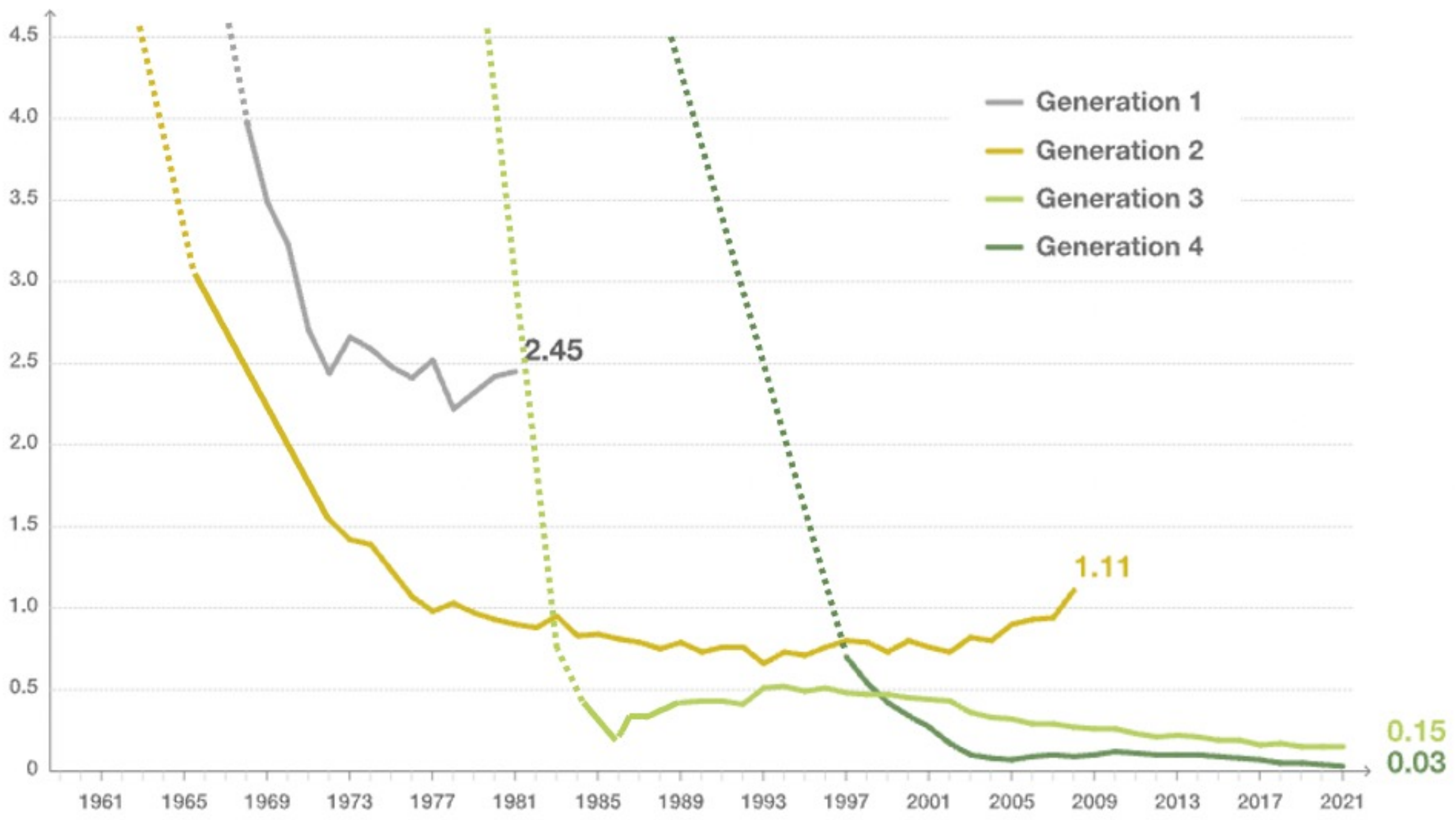
Summer 2025

NASA Integration Automation System- 2 (Flight Test?)



Aircraft Automation Development and Evaluation

Part 25 Fatal accident average rates



10 year rolling average aggregated rates based on Airbus safety reports, 2015-2022 (https://accidentstats.airbus.com/)

Automation Enabled Pilot

(AEP) Focus Areas

- Industry Representative Aircraft Control Concepts
- Concept of Operations and Evaluation of Aircraft
- Increasing Automation Capabilities
- Pilot Requirements

Background: Powered-Lift Aircraft

<u>Powered Lift Aircraft</u>

- Current state is UML 0.5
  - No FAA certified Powered Lift aircraft
  - AW-609 is in late-stage certification (UML-1)
    - turbine tilt-rotor

- Extensive government research into Tilt-Rotor configuration, one interface configuration

- Each Configuration has unique characteristics

- Next step How to make Powered-Lift Scalable
  - Existing Evaluation methods (i.e. Means of Compliance)

Lift Plus Cruise

Quadcopter

Tilt Wing/Rotor

eVTOL Flight Challenges

- Diversity in Proposed Aircraft Configurations
- Operations in Low speed and Hover will be restricted for many candidate eVTOL aircraft due to lack cyclic and/or collective control
- Powered Lift (e.g. Winged eVTOL) have additional challenges in transition
- Automation proposed to help with these challenges
    - All concepts currently proposing Indirect Flight Controls (IFCS)

Beta ALIA-250
(Lift + Cruise)

Joby S4 (Tilt Rotor)

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

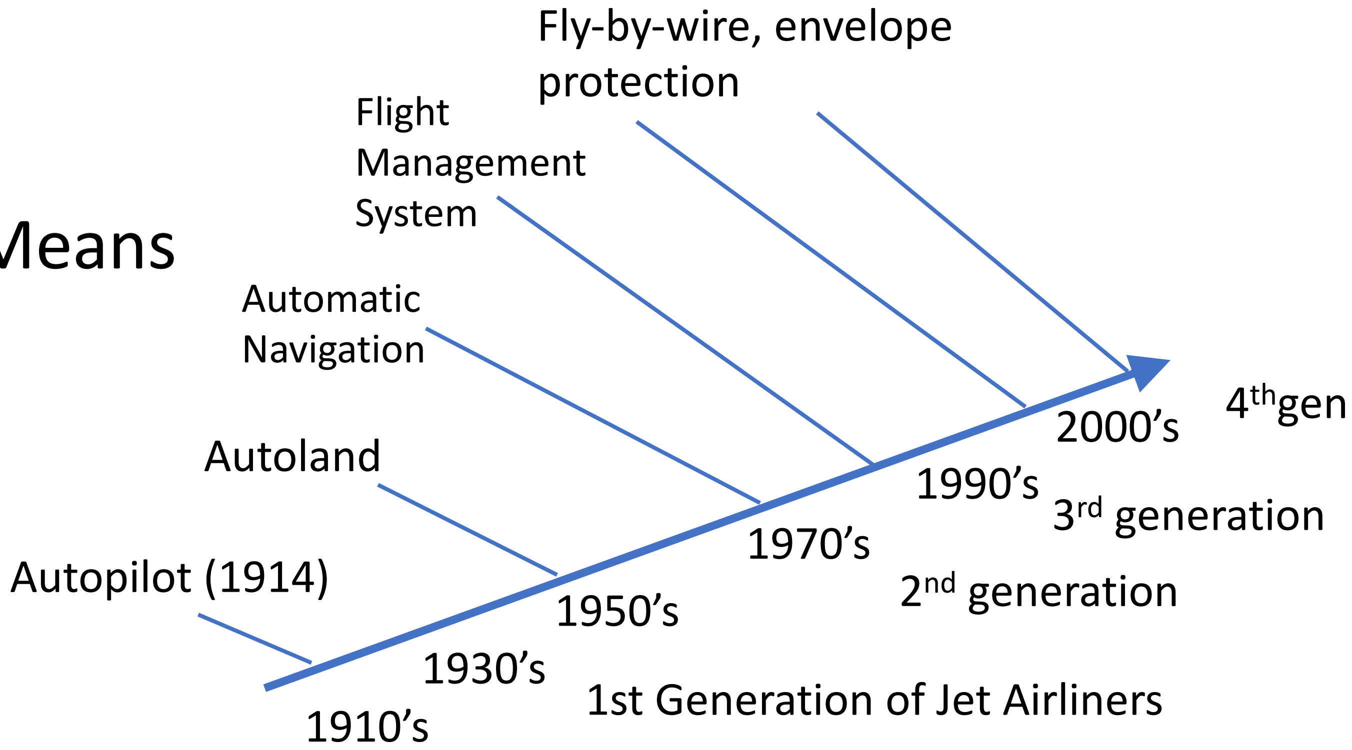
Archer Maker
(Tilt Rotor Hybrid)

Wisk Cora (Lift + Cruise)

Background: Automation

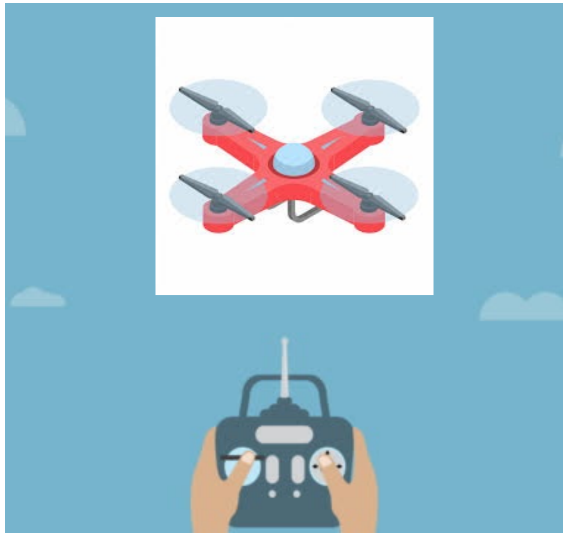
- Automation may enable new operations but also introduces new challenges
  - Slower response

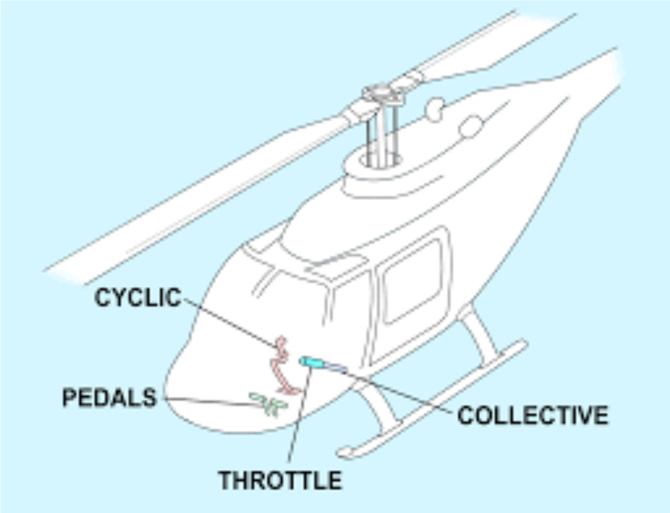
- Existing Evaluation methods (i.e. Means of Compliance) are inadequate



Background—-- Multi-Copter Drones vs Helicopters --

Small multi-copter drones are controlled by electric motors that change the RPM of individual rotors, meanwhile helicopters are controlled by changing the pitch angle of individual blades.





- Individual Rotor RPM control
- Differential thrust = slow response, but
- high (2 – 8:1) power to weight ratio
- smaller moment arm = faster response

- Low power to weight ratio (0.25:1)
- Cyclic and Collective control = faster response

- Low power to weight ratio (0.25:1) = slower response
- Differential thrust control = slower response
- Longer moment arm = slower response

Means of Compliance

Standard

- Ruler

- FAA role

- NASA role

- Aircraft Configuration, CC, AP, IC, DC, FM

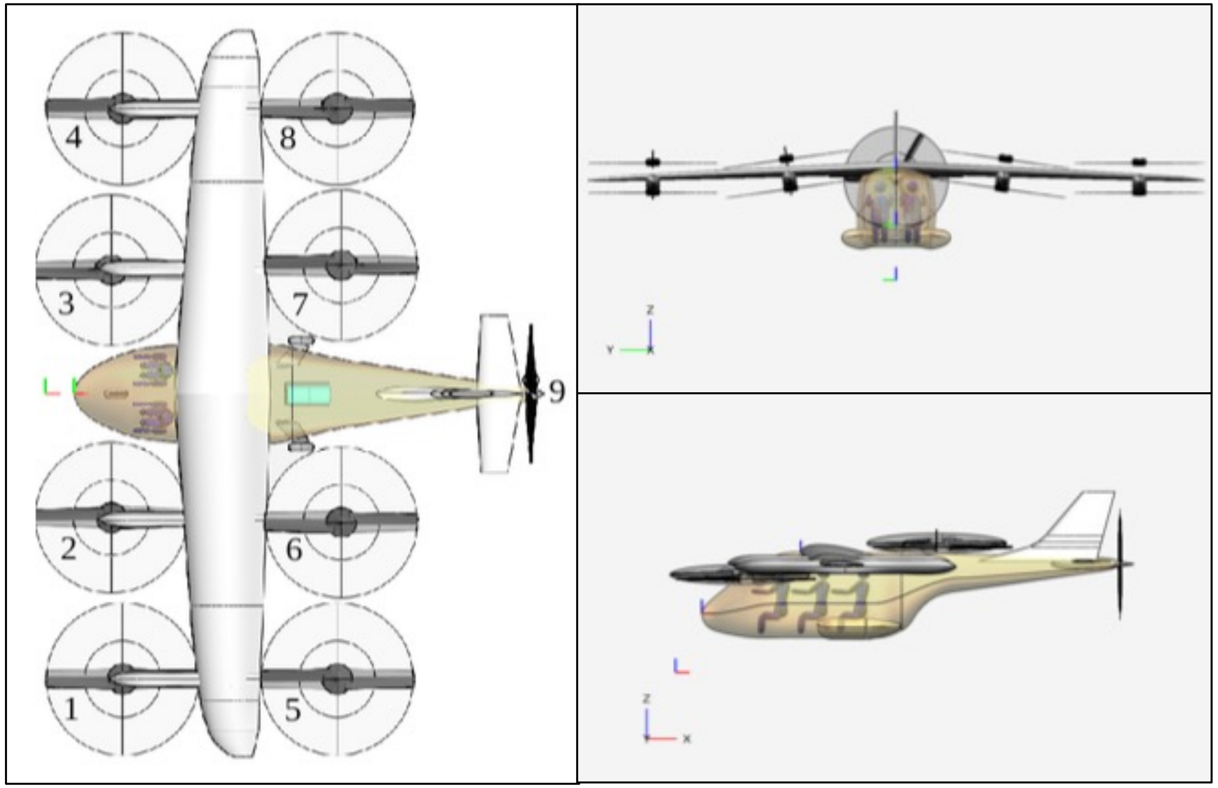
Concept of Operations

- Some AAM Concepts of Operations may be incompatible with proposed aircraft

Lift Plus Cruise (LPC) Vehicle Model

The RVLT turboelectric Lift Plus Cruise (LPC) concept model was designed and developed using the NASA Design and Analysis of Rotorcraft (NDARC) tool, and the quasi-Linear Parameter Varying (qLPV) dynamic model was generated by Advanced Rotorcraft Technology (ARC) using FlightLAB.

- Vehicle Configuration
    - Designed Gross Weight = 6013 lbs
    - Payload = 1200 lbs
    - 8 RPM controlled lifting rotors
    - 1 collective controlled pusher propeller
    - 2 ailerons, 1 elevator, 1 rudder
- Performance Parameters
    - Range = 50nm
    - Best endurance speed (@ 6,000 ft) = 90 kts
    - Best range speed (@ 6,000 ft) = 122 kts
    - Maximum speed (@ 6,000 ft) = 123 kts

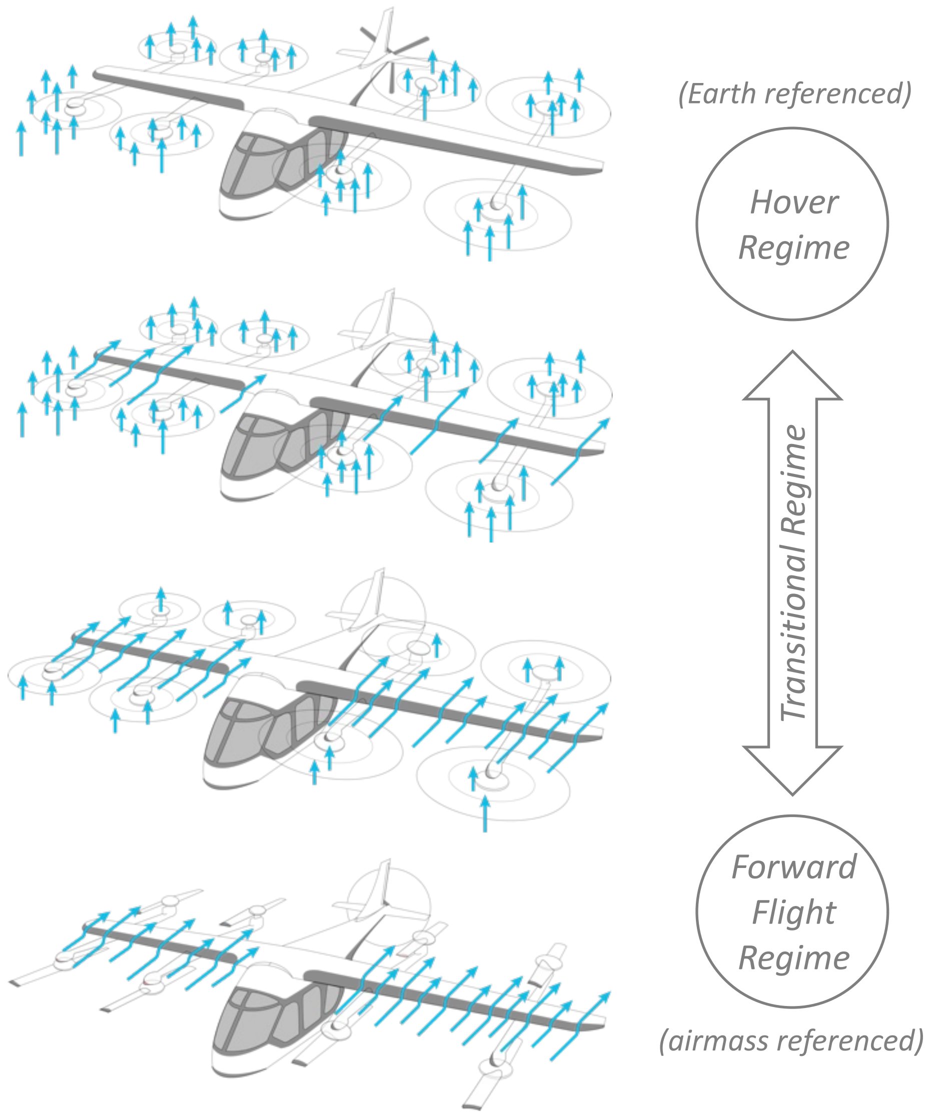


Silva, C., Johnson, W., Antcliff, K., and Patterson, M., "VTOL Urban Air Mobility Concept Vehicles for Technology Development", AIAA 2018-3847, June 2018.

Advanced Rotorcraft Technology, Inc., "Flight Control Models for a Concept Vehicle", SBIR Phase III 80NSSC19C0003 Final Report, March 2019.

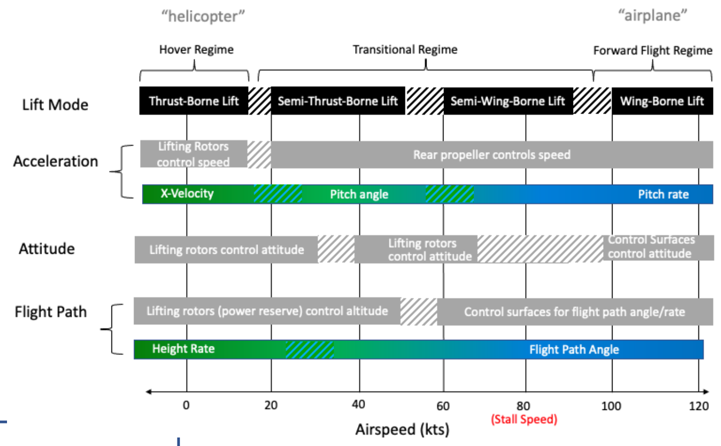
Winged eVTOL Taxonomy

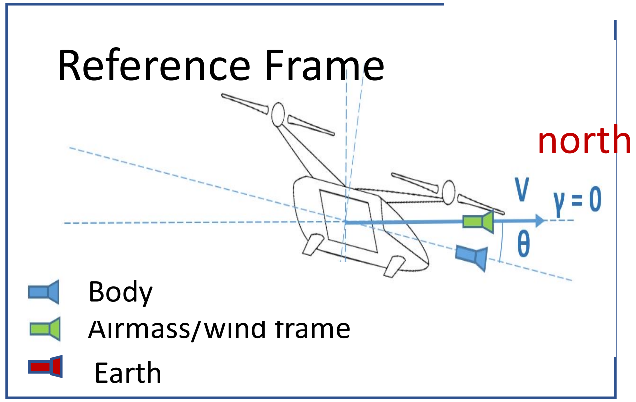
- Thrust Borne Lift
  - Lifting rotors provide lift
  - Vehicle pitches to vector thrust (e.g., for level acceleration)
  - Airframe produces minimal aerodynamic effects
- Semi-Thrust Borne Lift
  - Lifting rotors provide primary lift
  - Vehicle primarily increases thrust for level acceleration (e.g., via pusher prop, tilted rotors)
  - Airframe produces moderate aerodynamic effects (i.e., requiring AoA and sideslip considerations)
- Semi-Wing Borne Lift
  - Airframe provides primary lift
  - Vehicle increases thrust for level acceleration
  - Lifting rotors provide some lift (e.g., for AoA protection)
- Wing Borne Lift
  - Airframe provides lift (e.g., lifting rotors are stopped or tilted forward)
  - Vehicle increases thrust for level acceleration

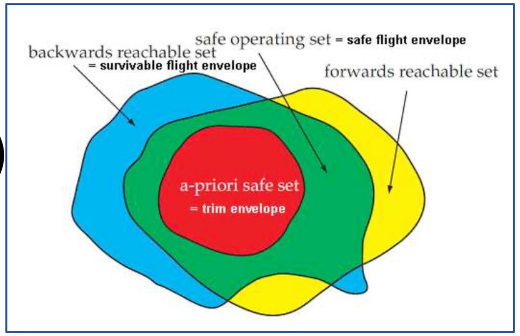


Aircraft Performance and Control: Lift + Cruise Example

- **Lift – Mode Transitions**
  - Thrust <> Semi-Thrust <> Semi-wing <> Wing Born lift source
- **Reference frames**
  - Earth/Airmass/Body frame
- **Response Types (RT) and RT combinations**
  - e.g. Rate vs. attitude
- **Control Modes**
  - RCHH, FPA
  - Tactical, strategic
- **Displays**
  - Information integration and alerting
  - Display components (e.g pitch/Flight path centric, display guidance displays)
- **Envelope protection**
  - Behavior at transitions

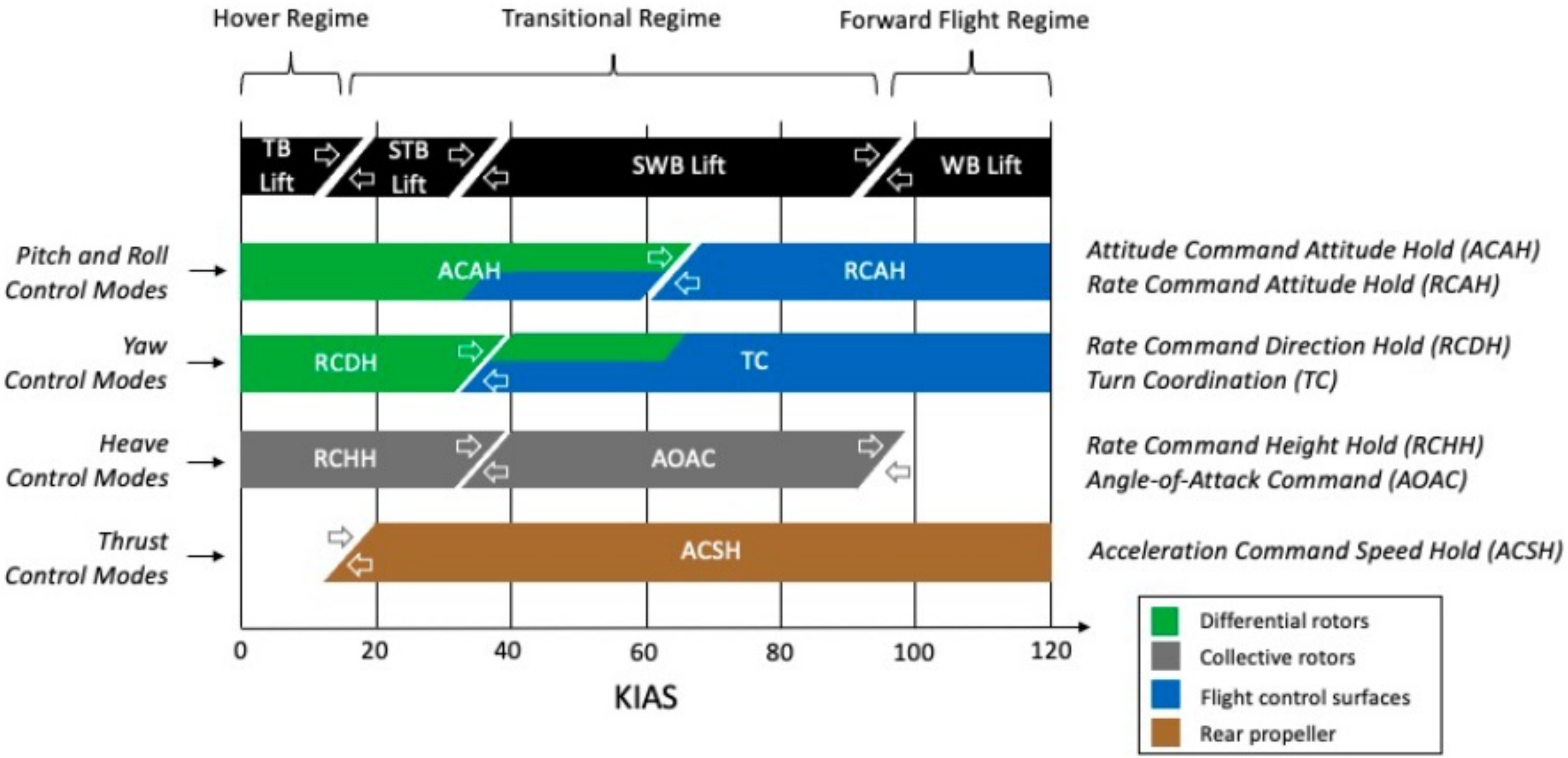






IFCS Control Implementation

- Instantiation for LPC, but can be used for other aircraft configurations
- Identifies transitions, which require special attention for evaluation
- Transitions are aircraft agnostic



eVTOL Flight Challenges

- Diversity in Proposed Aircraft
- Operations in Low speed and Hover will be restricted for many candidate eVTOL aircraft due to lack cyclic and/or collective control
- Powered Lift (e.g. Winged eVTOL) have additional challenges in transition
- Automation proposed to help with these challenges
  - All concepts currently proposing Indirect Flight Controls (IFCS)
- Existing Means of Compliance Inadequate for IFCS and increasing automated functions
  - IFCS airplanes have only certified under Special Conditions
- Evaluation methods will need to cross airworthiness and operations

Beta ALIA-250
(Lift + Cruise)

Joby S4 (Tilt Rotor)

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

Archer Maker
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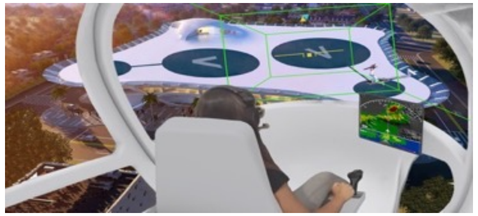
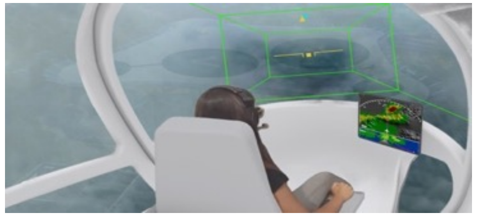
Proposed Pilot Automation Interaction (PAI) Framework

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

Autopilot Command
(Human-On-the-Loop)



Task Management
(Human-Over-the-Loop)



Mission Management

PAI -6
Autonomous Aircraft Operations
i.e., no real-time intervention capability required

PAI-0

Axis Control
e.g., "Conventional" Stability augmentation, requires quick response, conventional interfaces

PAI -1

Vector Control
e.g., Indirect Flight Control (may include some hybrid functions with axis or target control)

PAI -2

Target Command
e.g., Autopilot With no Flight Path Management

PAI -3

Path Command
e.g., Autopilot with Aircraft Flight Path Management

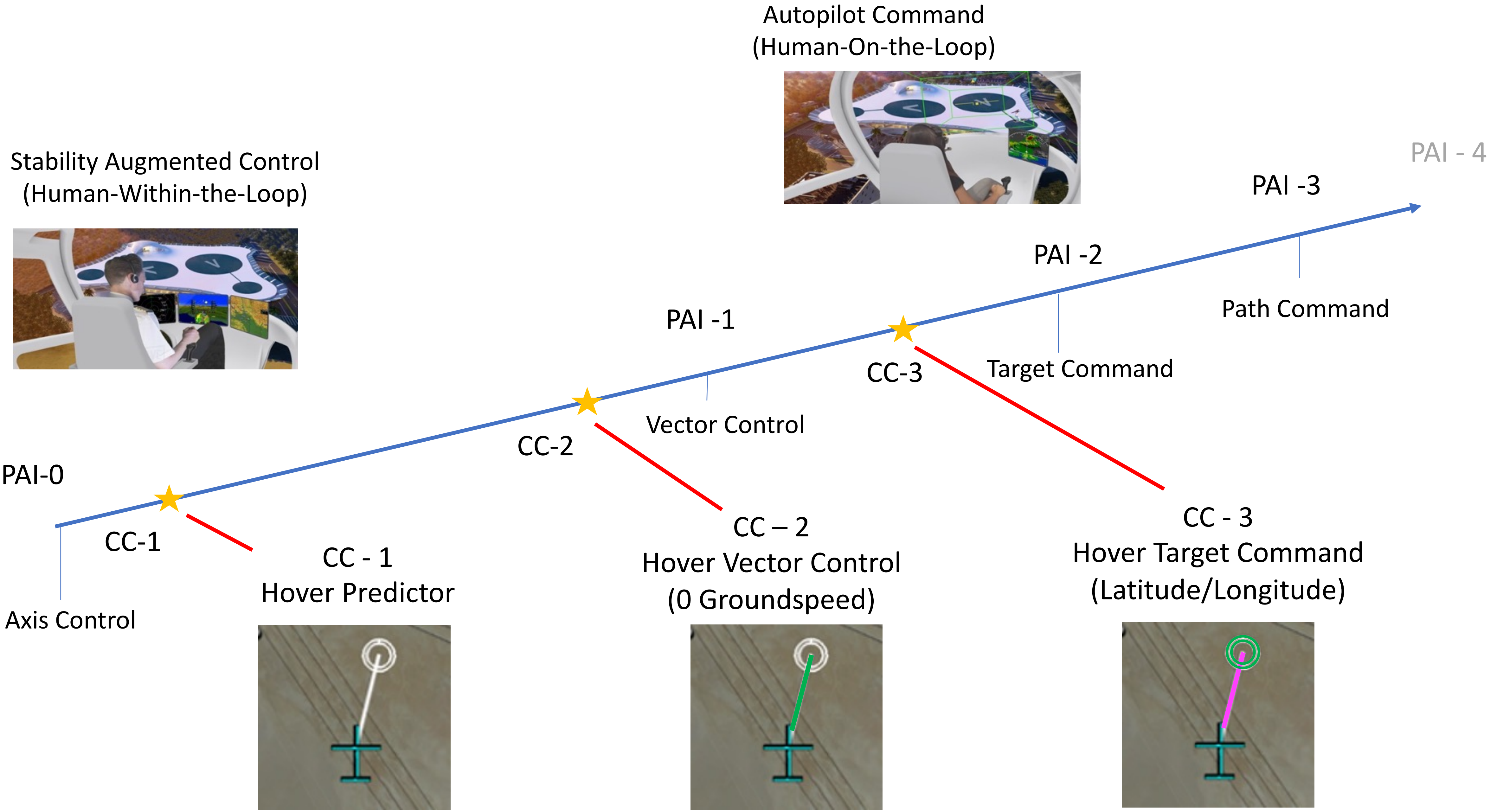
PAI -4

Task Management
e.g., Integrated aircraft automated functions including response to hazards

PAI -5

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

AEP – 1 Investigation



Automation Enabled Pilot Study 1 (AEP-1)

- **Goals:**
  - Develop and assess representative VTOL aircraft and aircraft automation
  - Validate evaluation measures and revise ConOps requirements

- **Objectives -** Evaluate challenges associated with:
  - Limited hover controllability
  - Transitions between forward and vertical flight
  - Varying levels of automation and use of automated functions

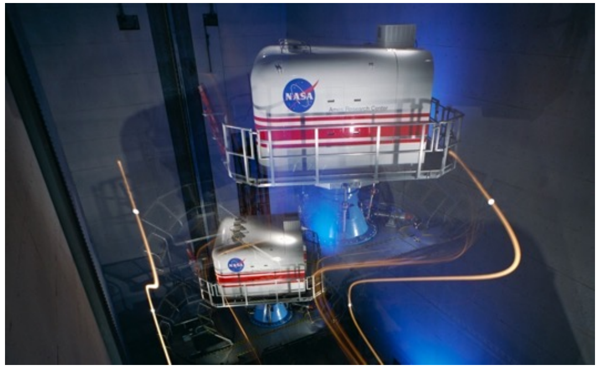
- **Approach**
  - Utilize industry representative eVTOL aircraft models in collaboration RVLT
  - Implement Automation Command Concept (CC) technologies
  - Evaluate in Fixed-Base and Vertical Motion Simulator (VMS)

Quadcopter

Lift Plus Cruise

Desktop Development

Fixed-Base
Development and Test



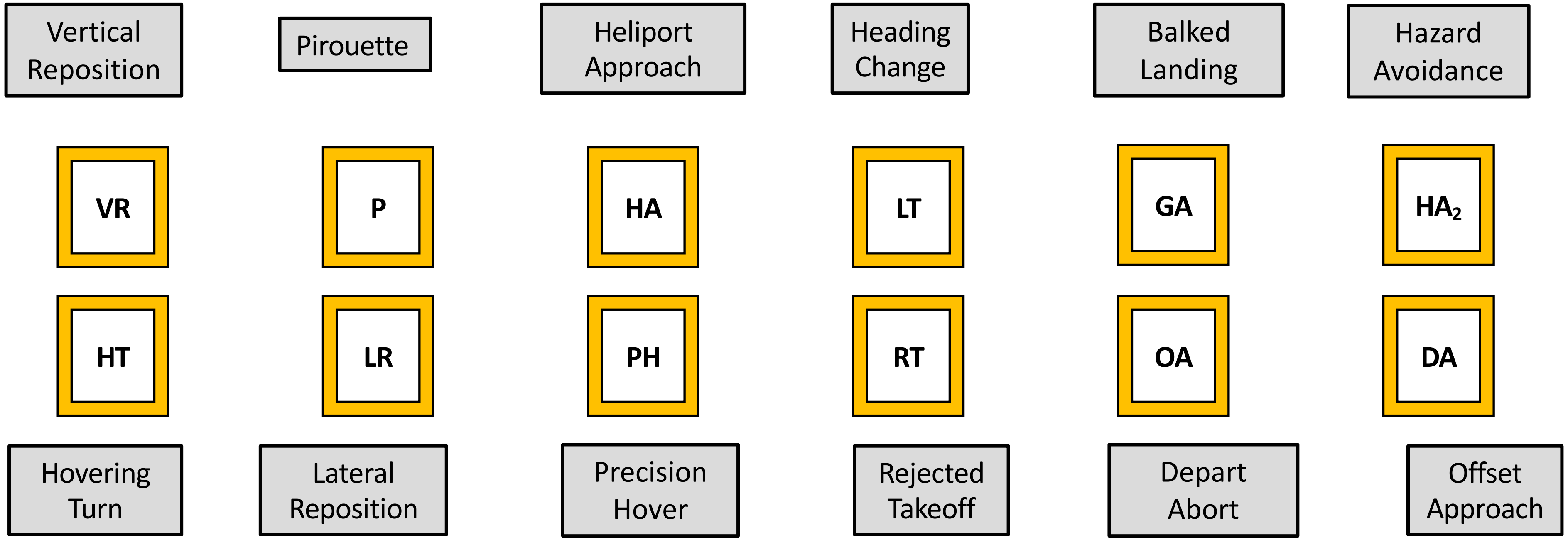
Flight Test Maneuvers (FTM)

- Catalog of FTM developed for military evaluation of IFCS and advanced automated control as an FAA Means of Compliance.

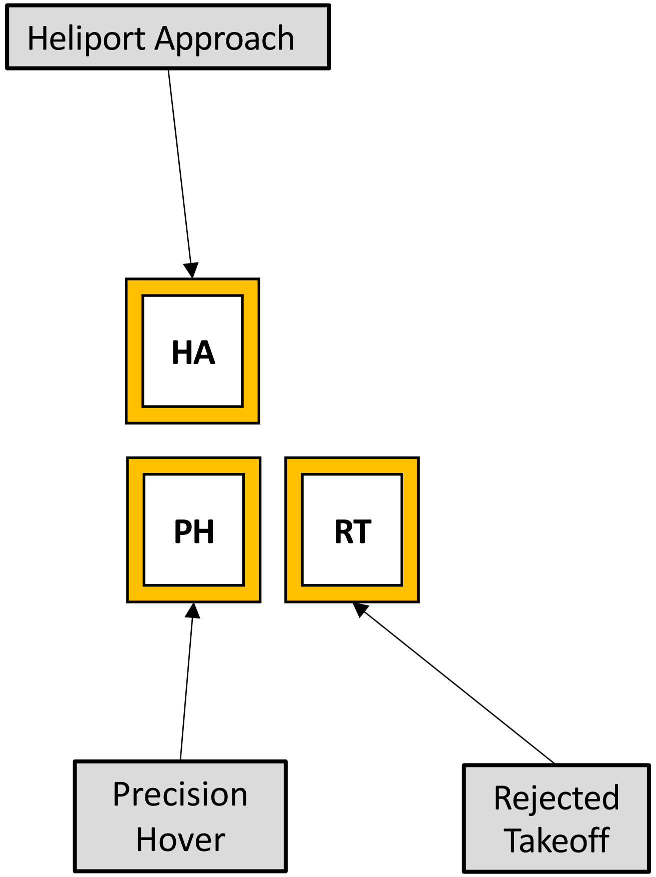
- Maneuvers and Performance Criteria are based on expected Concept of Operations

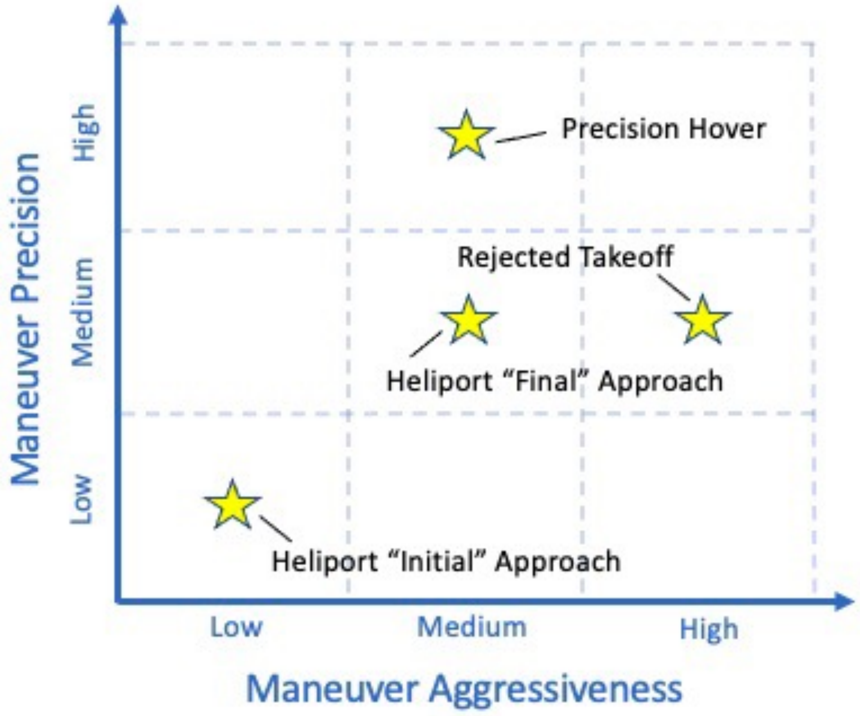
- Maneuvers are designed to:
  - Expose deficiencies in aircraft controllability
  - Be agnostic to aircraft and automation configuration (including inceptors)
  - Stress test aircraft and automation configuration in operationally representative maneuvers (e.g. high gain and low gain,

- Performance criteria are designed for expected:
  - Environmental conditions



AEP – 1 Evaluation Flight Test Maneuvers (FTM)





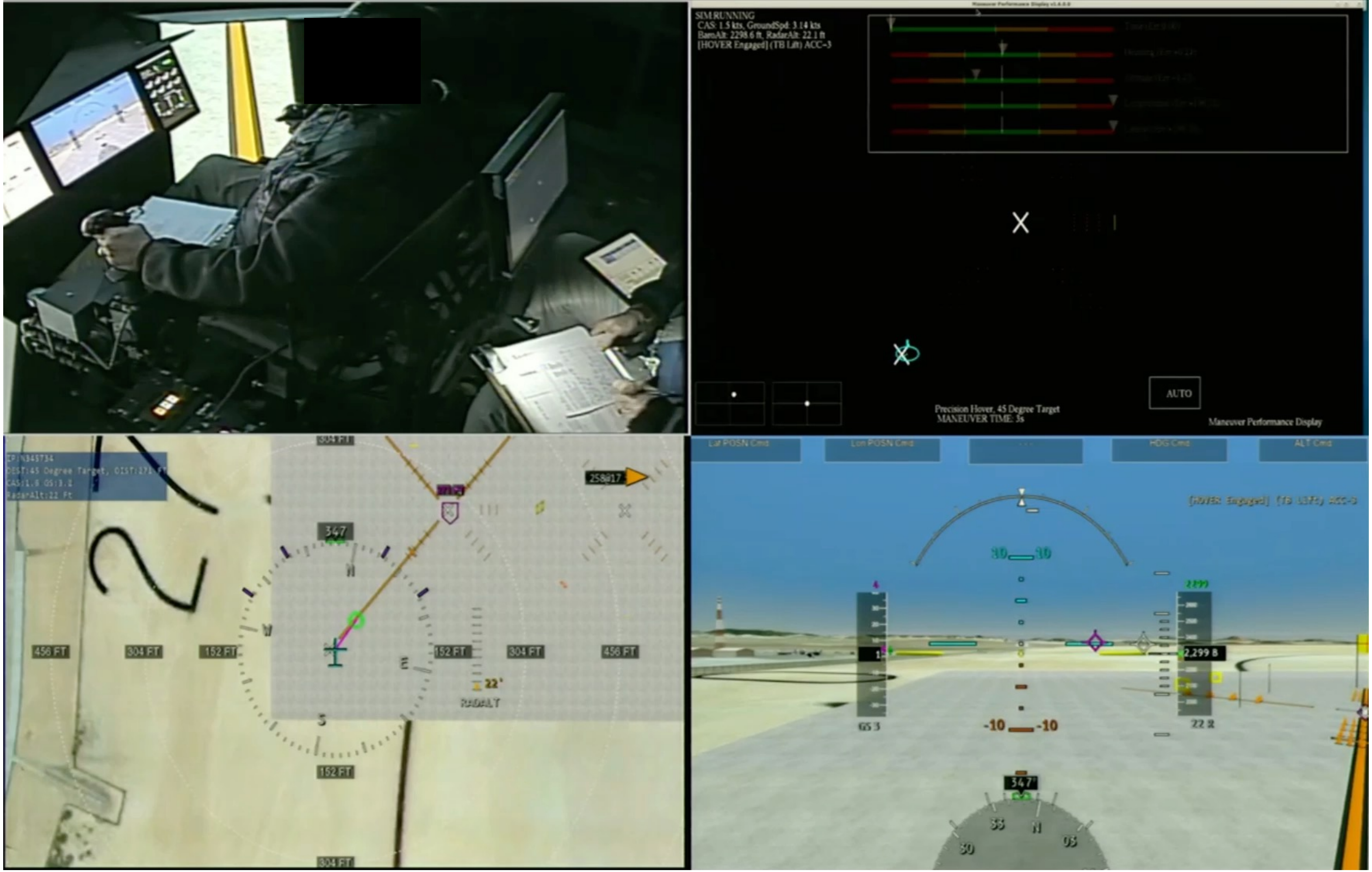
AEP-1 Study Summary

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

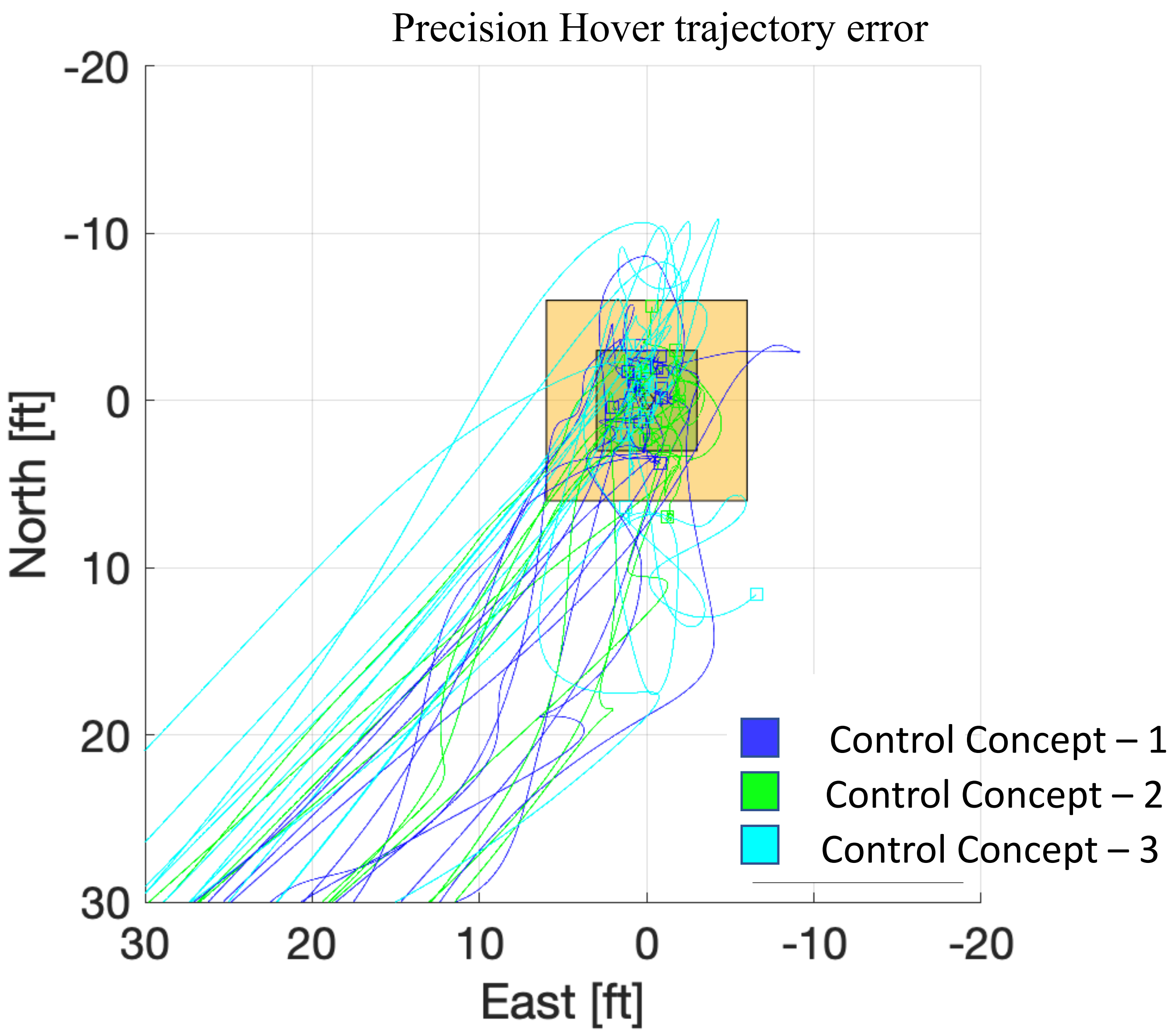
Test points
- 102 data points collected
  - 3 industry representative Automation Control Concepts
  - 3 Maneuvers (Takeoff, Approach, Hover)
  - 2 conditions each (calm, 17 knot wind)

High Points
- Automation Control Concepts, inceptors and displays were flyable, valid and representative
- Desired performance levels were achievable for each maneuver
- Many task – inceptor combinations were not certifiable as implemented
  - "Flyable but not certifiable"

Precision Hover



Precision Hover Results (Automation Condition)



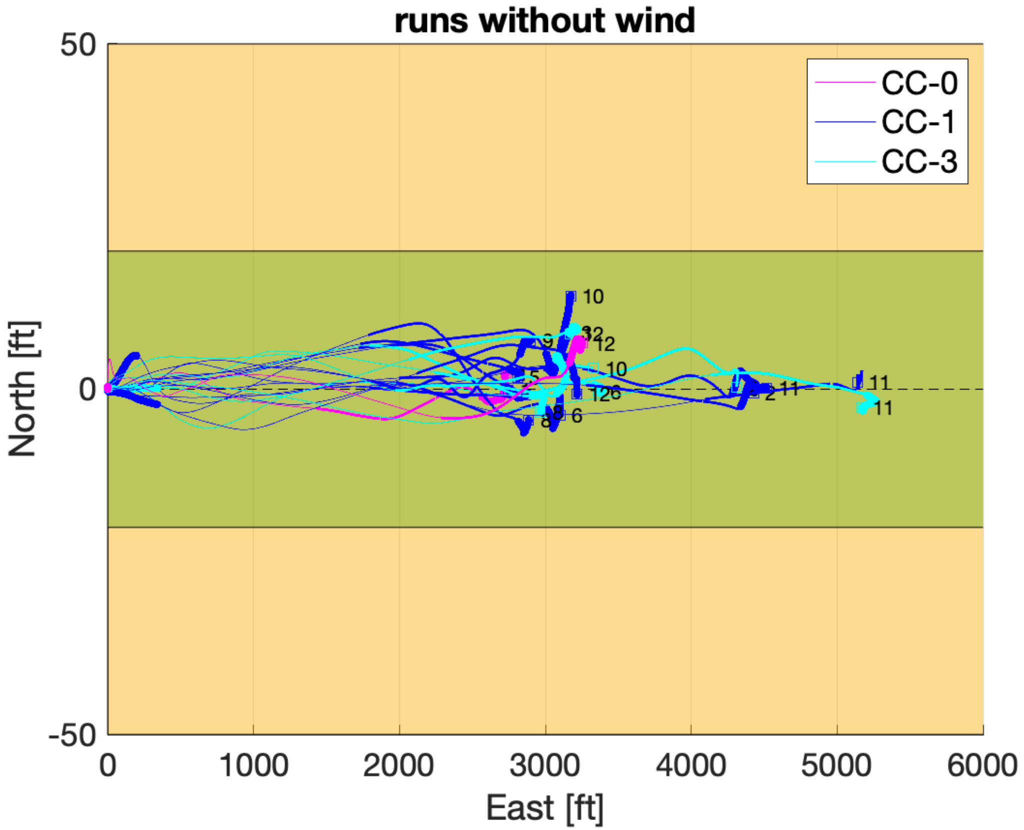
CC-3 quote

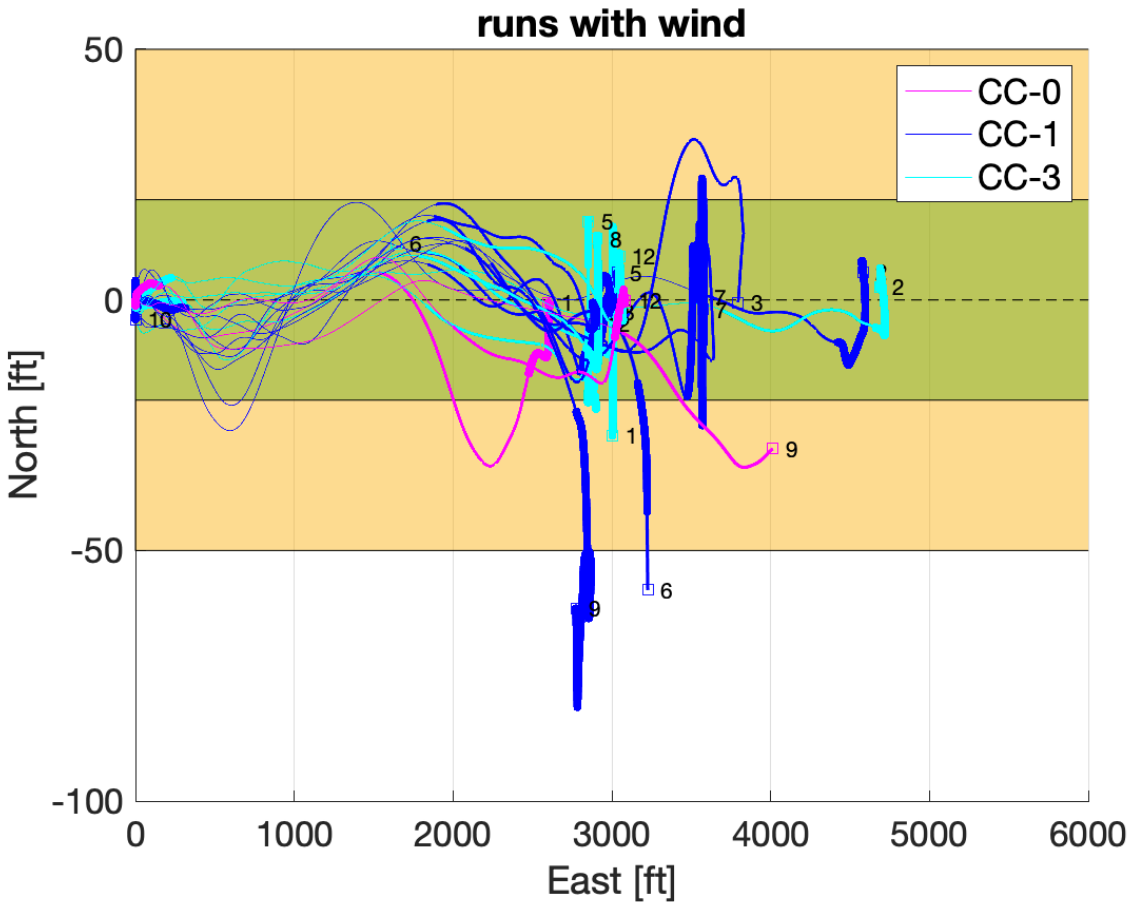
“Not possible to meet the performance criteria without using the display…”

Rejected Takeoff

Autopilot flying Rejected Takeoff in crosswind

Rejected Takeoff (Automation Condition)

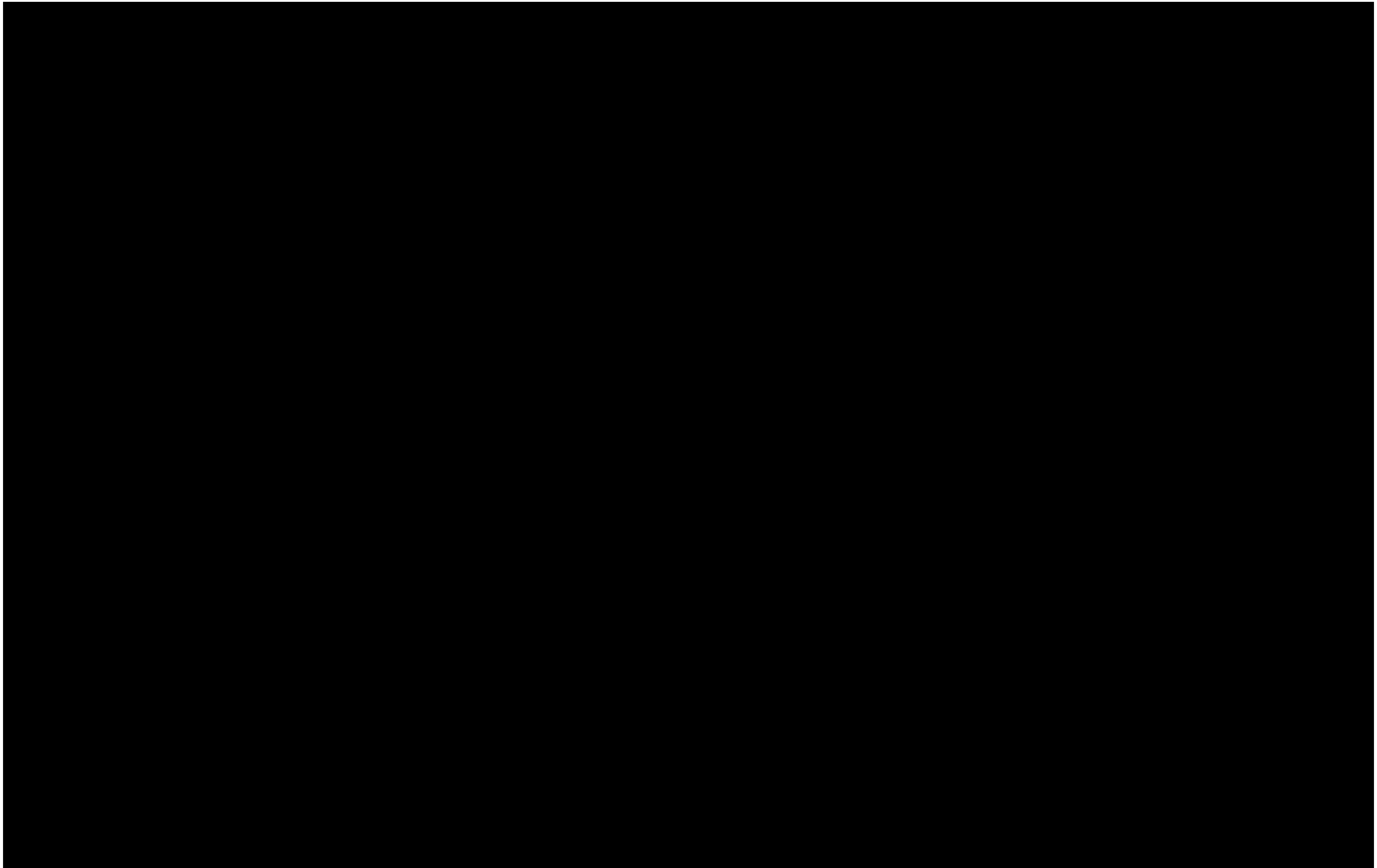




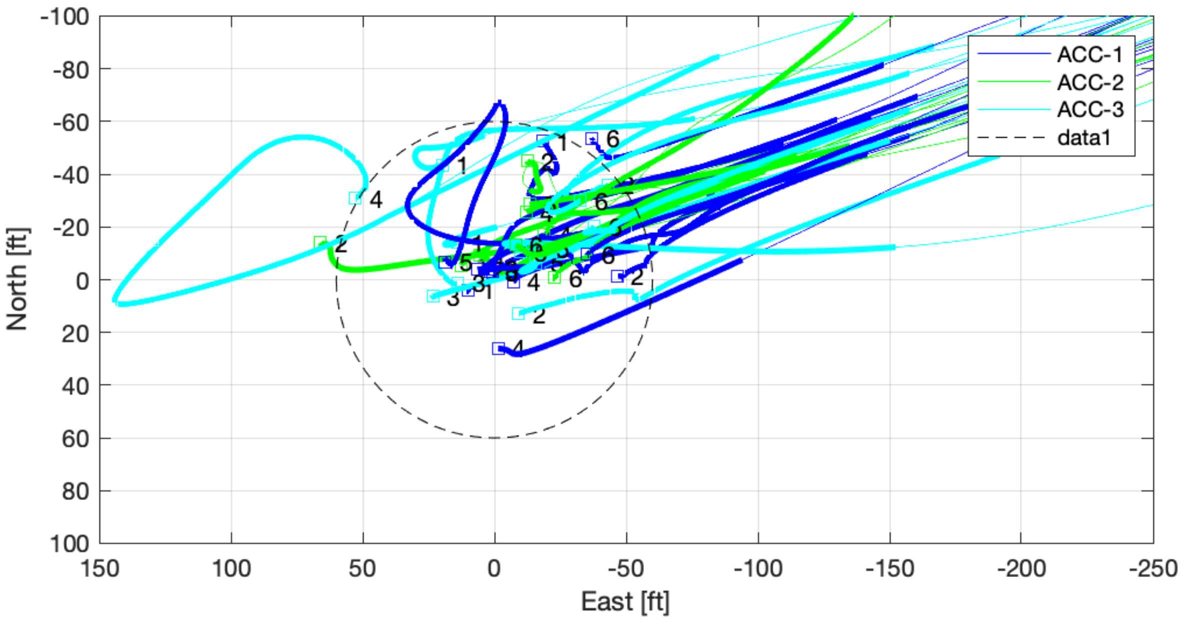
"This is a completely different task with winds"

"My company's aircraft may struggle with this maneuver"

Heliport Approach



Heliport Approach (Automation Condition)



• Figure . Heliport Approach trajectory error (automation condition)

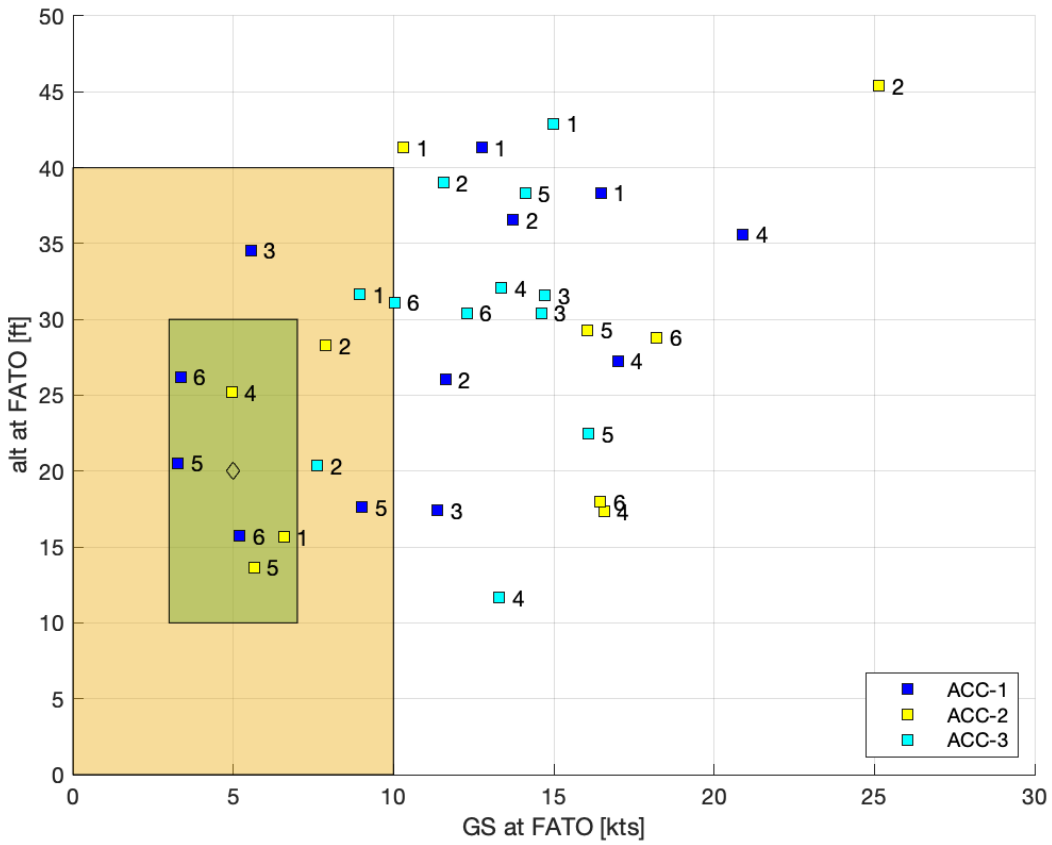
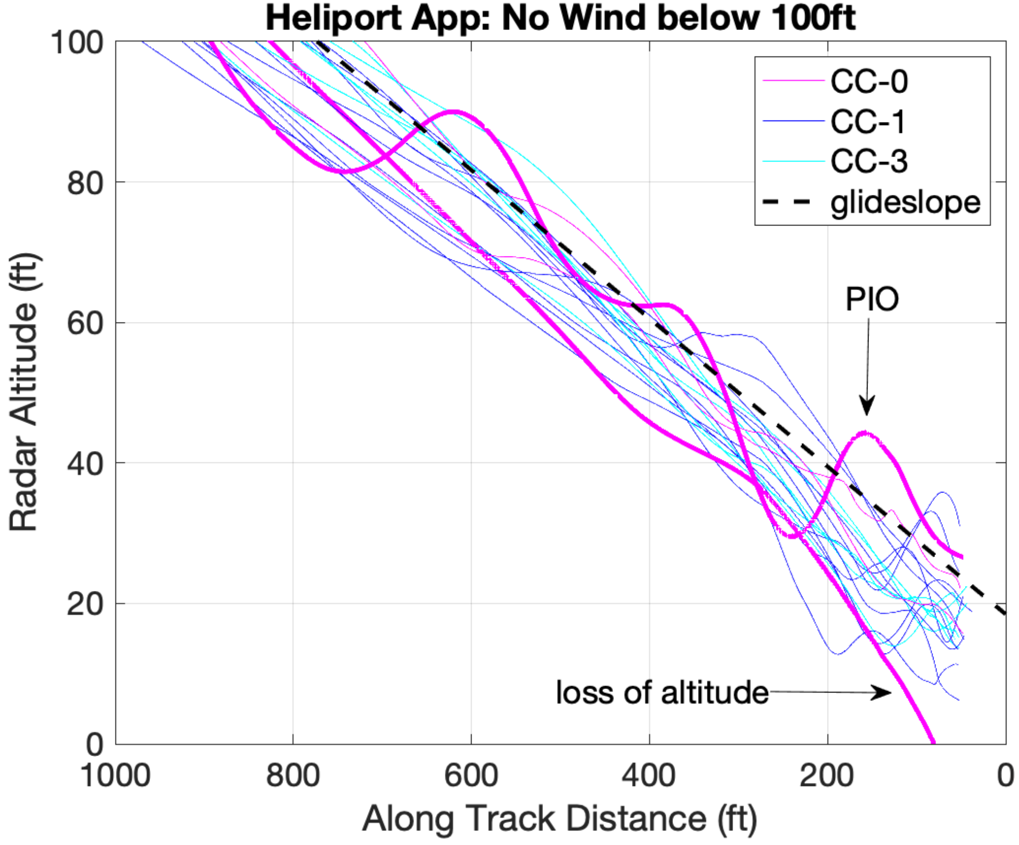
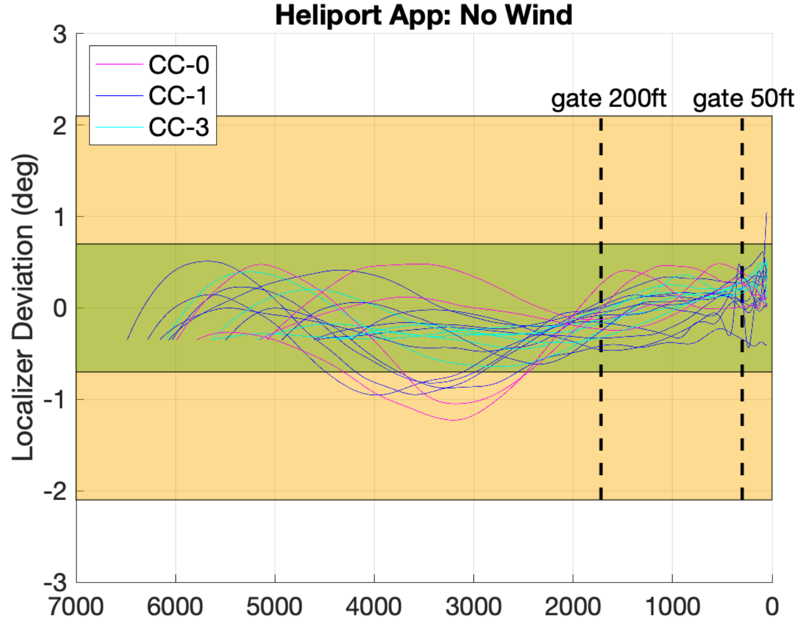
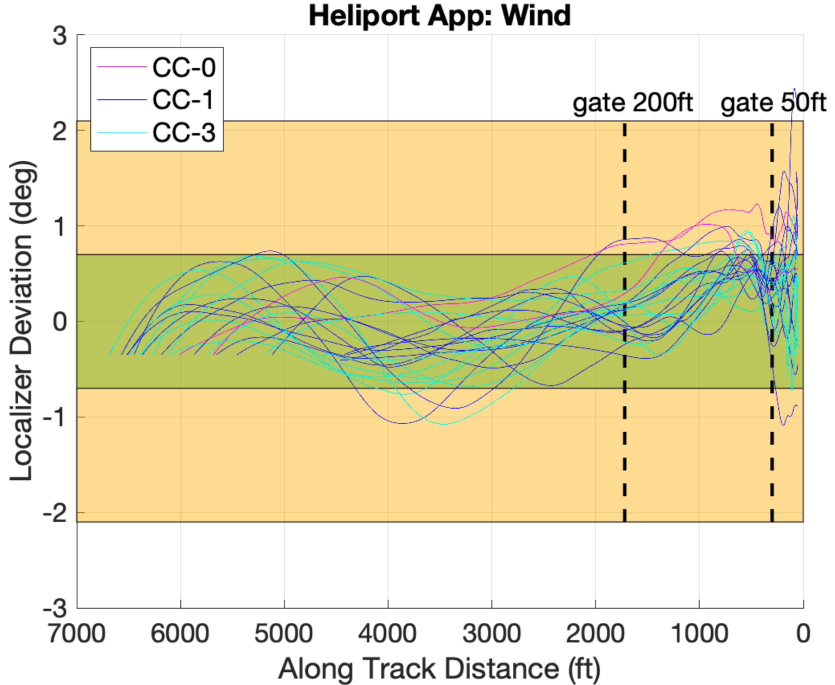


Figure . Distance from FATO boundary at end of Heliport Approach (automation configuration)

Heliport Approach (FAAVE-2 Automation Condition)







Heliport Approach Quotes

“had to learn to get out of the way of the automation…”

“Automation changes the task”

“negative habit transfer…”

CC -2

“had to change inceptor strategy during the approach, once TRC mode engaged”

CC-3

“desired performance but I feel like it was luck, it was uncontrollable through the transition”

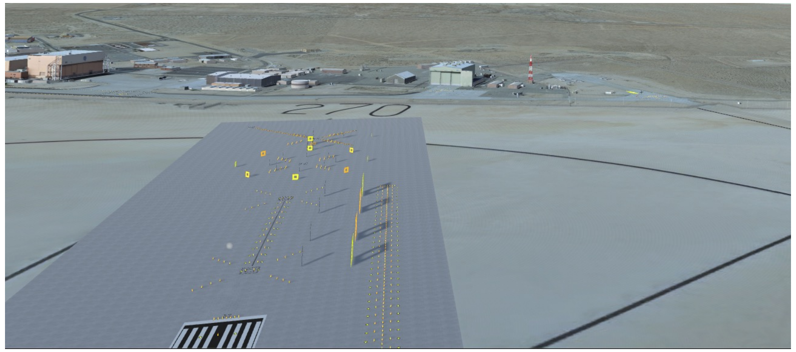
“ couldn’t predict the behavior of the aircraft…”

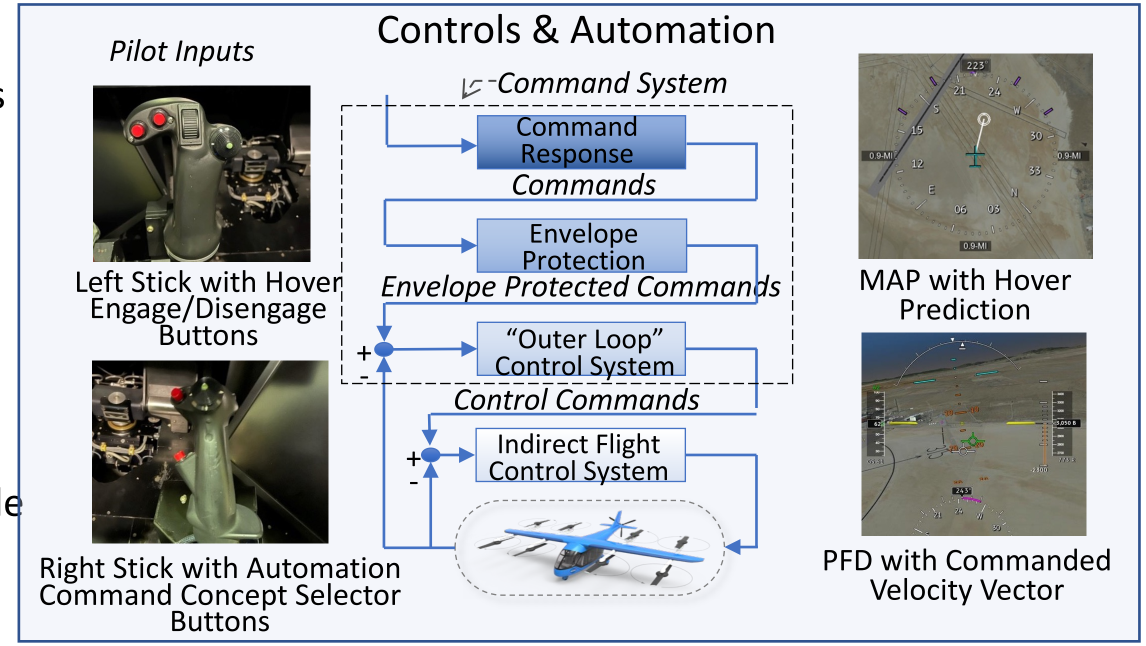
AEP -1 Simulator Development Accomplishments

- **Challenge:**
  - No civilian requirements for simulated VTOL test environment
- **Accomplishment:**
  - Developed visual environments, including virtual test course with enhanced Usable Cue Environment (UCE) with additional furniture (e.g. Hover Boards) as a baseline for FAA applicants
- **Challenge:**
  - No existing industry representative VTOL aircraft performance and flight control system for developing evaluation methods
- **Accomplishment**
  - Developed IFCS flight control system for RVLT VTOL performance models
- **Challenge:**
  - Industry representative aircraft automation and pilot interfaces
- **Accomplishment**
  - Developed multiple industry representative control and inceptor configurations
  - Developed baseline Primary Flight Display, Map display, prototype vehicle health display and flight test performance display
  - Developed evaluation framework and supporting test materials


Quadcopter


Lift Plus Cruise





Takeaways

- Aircraft concepts developed and used in the study were industry representative
  - Feedback from industry test pilots with similar aircraft
- Simulator capabilities and test range provided reference for industry
  - Several requests from industry
- Aircraft Response and Automation change the nature of task
  - Lift Plus Cruise configurations may have difficulty with UAM operations
  - Automation helps with precision, but not aggressiveness
  - Example: Precision Hover CC -3 required use of HMD
- Evaluation and Concept of Operations
  - Dictate precision and aggressiveness requirements
  - Aircraft capabilities must be aligned with Operational requirements
    - Difference between Flyable and Certifiable
  - Example: Rejected Takeoff (wind made big difference) PH (wind made little difference)
- Evaluating New and Novel Automation and Pilot Interfaces
  - Transition Decision Logic must be aligned with task and environment
  - Example: Heliport Approach Crab – Sideslip transition

Deliverables

(Foundation for future AAM development environment)

<u>Development of:</u>

- Representative eVTOL aircraft models
- Multiple Flight Control system configurations
- High fidelity urban visual scenery models for simulation
- Multiple Industry representative inceptor configurations
- Framework for describing Flight Control system
- Framework for describing inceptor configurations
- Test course specification
- Test course furniture definition (e.g. hover boards)
- Evaluation metrics

<u>Pending Publications:</u>

- Conference papers (AIAA Aviation)
- NASA Technical Reports
- FAA technical reports
- ASTM standard (for IFCS)
- Control allocation and control mode schedules for eVTOL aircraft
- Inceptor configurations