Training the Powered-Lift Evaluation Pilot

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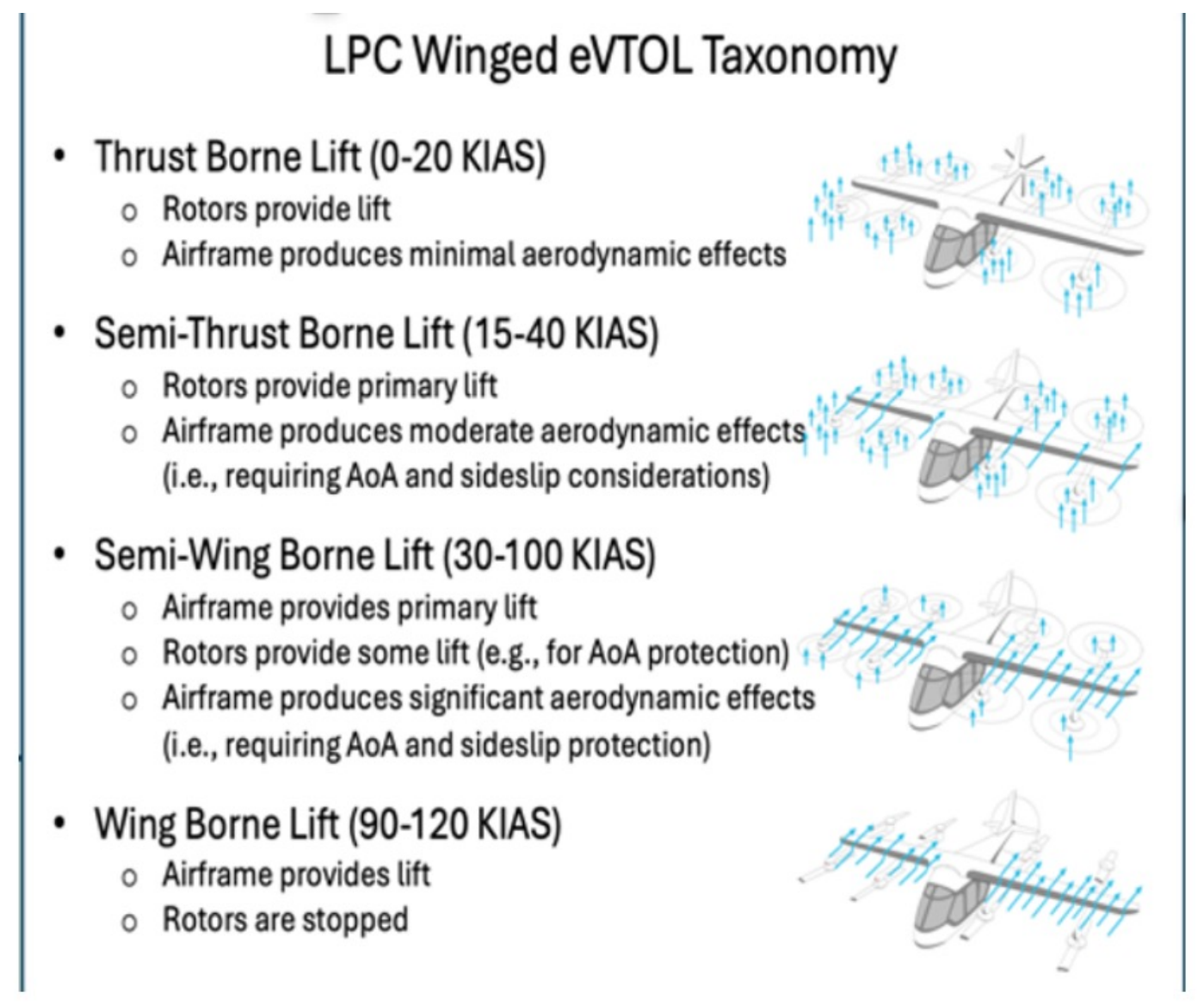
Abstract

This poster describes a project to prepare pilots for a study assessing novel aircraft automation concepts for electric Vertical Takeoff and Landing (eVTOL) aircraft using NASA's Vertical Motion Simulator (VMS). By exploring the operational and learning challenges related to transitioning between forward flight and vertical landing, we seek to establish baselines of pilot workload and aircraft handling qualities across varying atmospheric conditions and automation states. The simulated eVTOL design differentiates flight control allocations as a function of airspeed across four speed ranges as the vehicle transitions between fully thrust-borne lift and wing-borne lift. As speed increases, side stick controls command: translational ground speeds, vertical and lateral acceleration, vertical rate, vertical flight path angle, and bank angle. This novel approach to flight control allocation creates a significant learning challenge for pilots.

Since initial eVTOL aircraft may have limitations on hover capabilities, automation and flight guidance cues also vary with airspeed to provide efficient landing profiles while still providing cues suitable for cruise flight. The NASA team prepared the study pilots to follow these flight guidance cues along curved Required Navigation Performance (RNP) approaches and along 6° and 12° glide paths to energy-efficient assistive-hover landing and go-arounds. The pre-VMS preparation sought to prepare pilots from diverse levels of experience and background. To do this, NASA researchers designed and developed a fixed-based, large field-of-view simulator with terrain, structures, and air traffic. With one day of combined classroom learning and skill development in the fixed-base simulator, pilots were largely able to fly the simulated eVTOL in the VMS with sufficient mastery to provide handling quality assessments using the Cooper-Harper Handling Qualities Rating and workload assessments through the Bedford Workload Scale.

I. INTRODUCTION

The emerging sector of electric propulsion eVTOL aircraft, broadly defined by the Federal Aviation Administration as 'Powered-Lift' vehicles, is advancing rapidly with state-based Indirect Flight Control Systems (IFCS) integral for managing flightpath control [4]. These increasingly automated systems are designed for either single-pilot operations or fully autonomous flights within densely populated airspaces characterized by closely sequenced traffic patterns [5]. **Crucially, comprehensive evaluation pilot training is essential** (the word pilot also applies to personnel controlling autonomous operations) for safe and effective operation of these innovative aircraft. The precision in flight control is also critical especially during landings, hover/taxi maneuvers, and takeoffs particularly at elevated vertiports where pilots must contend with variable wind conditions, turbulence and traffic.


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

Fig 1. LPC Design Parameters and Lift Sources

II. EVTOL AIRCRAFT (THE TRAINING COMPLEXITY)

Among the operational complexities, the training of evaluation pilots lies within an interesting array of eVTOL designs, of which the Lift-Plus-Cruise (LPC) model is one [6]. This design not only presents a visually distinctive form factor utilized within the AEP-2 study but also has a complicated configuration featuring eight separate lifting elements with a dedicated rear propeller providing thrust. Figure 1 depicts how lift and thrust allocation varies with airspeed:

- **Below 20 Knots Indicated Airspeed (KIAS):** Rotors predominantly provide lift.
- **15-40 KIAS:** Wings begin to influence aerodynamics in the range.
- **Above 30 KIAS: L**ift can shift to become primarily wing borne.
- **90-120 KIAS:** Wing borne lift becomes exclusive at at which point the rotors cease operation.

Wing-borne flight is more energy-efficient, requiring less battery power compared to lower airspeeds where rotor-based lift is employed.

LPC Control Allocation: Figure 2 illustrates the speeds at which different thrust methods (rotors and propeller) and surface controls impact vehicle control. It also designates flight regimes such as the hover, translational and forward flight regimes and differences regarding controls between increasing and decreasing speeds.

Pilot Control Commands and Lifting Modes: Table 1 provides example insights into changes in pilot control commands (e.g., speed, acceleration, rate) and lifting modes (for one of three specific automation study conditions) based on aircraft speed. Onset speeds for both the lifting modes and control commands vary and blend into effect at different speeds depending on whether the vehicle is accelerating or decelerating.

IFCS Integration. With over 400 unique eVTOL (electric Vertical Takeoff and Landing) concepts being planned worldwide, the evaluation pilot understanding associated with integrating IFCS alongside automation solutions is critical. As the development of state-based control systems enables the possibility of simplified aircraft control, it also ushers in novel pilot automation, new operational concepts, and new flightdeck interfaces such as unconventional flight inceptors, and unique displays. These efforts address inherent challenges associated with controlling innovative aircraft. Ultimately, evaluation pilot training will play a pivotal role in advancing this field.

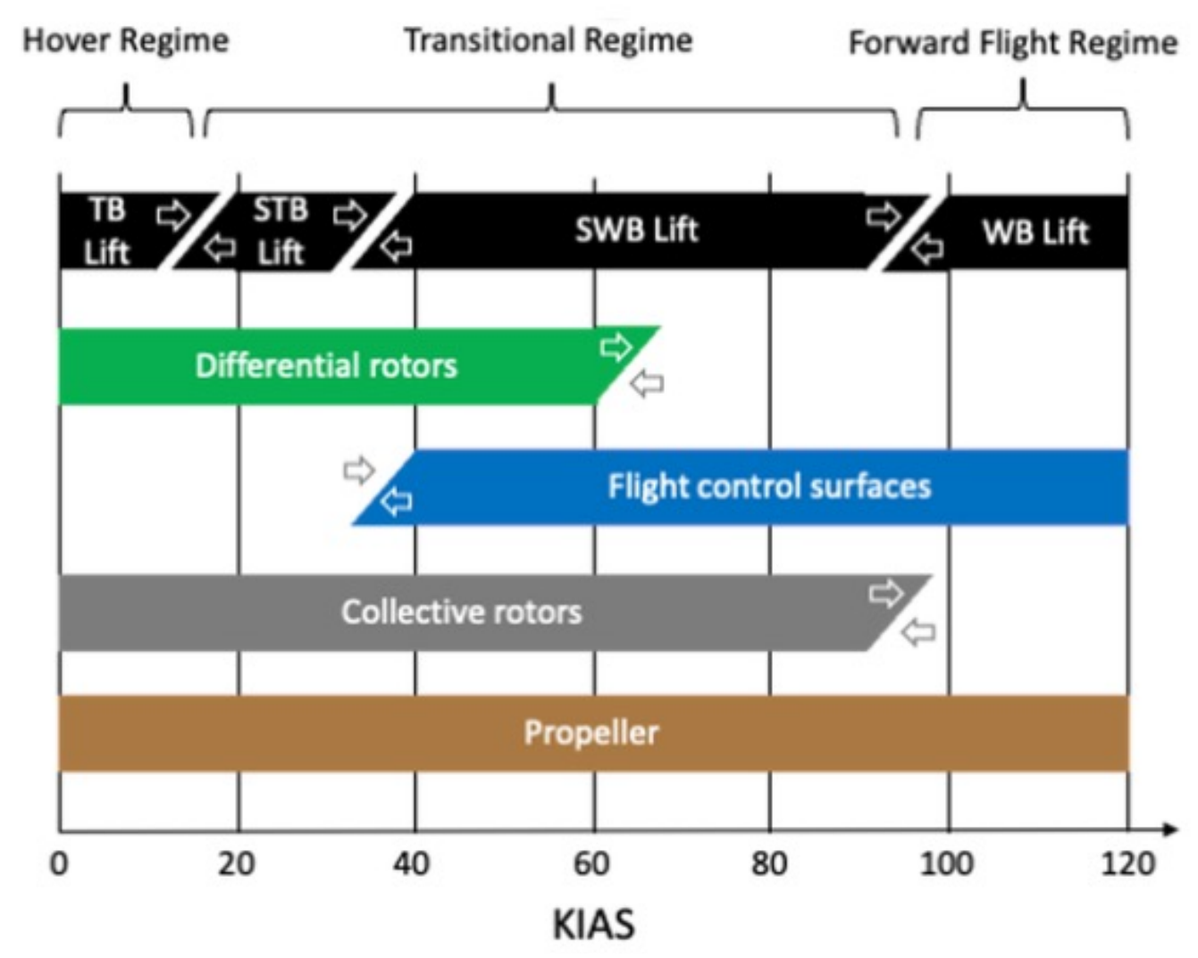


Fig 2. Control Allocation Schedule (lift source, control surfaces, and propeller thrust)

III. PILOT TRAINING

The training program had broad objectives: to prepare evaluation pilots for flying and rating novel eVTOL approach scenarios on NASA's large motion base Vertical Motion Simulator (VMS) [7]. Individual on site pilot training initially took place in a classroom adjacent to Aerospace Cognitive Engineering Lab - Rapid Automation Test Environment Simulator (ACEL-RATE) , shown in Figures 3 and 4, which was designed for this research. Before arriving at the simulator, an Aircraft Flight Manual (AFM) was available for pilots to review along with other administrative instructions. The AFM served as a valuable resource, not only helping pilots understand the eVTOL simulation model but also providing fundamental information for distributed researchers involved in simulation planning and execution. It often clarified the functions of last-minute changes.

The training modules were designed to instill a positive constructive outlook, ensuring that by the end of the instructional period, evaluation pilots would possess the proficiency to control the simulated aircraft. This included executing test maneuvers across a spectrum of environmental scenarios and gaining an understanding of the assessment methodologies. Adequate time was allocated for an review of each evaluation pilot's history, encompassing their familiarity with automated systems, input devices, regulatory frameworks, interfaces, and pertinent information displays such as flight directors and navigational maps. This personalized approach allowed for a tailored training experience.

Furthermore, participants were apprised of the AEP-2 study's aims, the chronological breakdown of activities, and briefed on both the ACEL-RATE Simulator's environment and its interface features. Videos of approach scenarios were especially useful for pilot understanding during the evaluation pilot training. Outlines for both classroom sessions and practical simulator-based sessions are provided as follows:

1. Advance email correspondence: Introduce the vehicle and control concepts. Provide a virtual Aircraft Flight Manual (AFM).

2. Combined classroom and fixed-based simulator session at Ames Research Center:
   - Instruction tailored to the participant's experience level and aircraft category background.
   - Simulator visual cues and flight displays.
   - Expanded explanation of flight control allocation
   - Hover and translation practice.
   - Approach and landing practice.
   - Flight guidance cues and application to assisted hover.
   - Flight guidance cues during RNP approaches.
   - Auto-hover selection and path correction.
   - Introduce Cooper-Harper Handling Qualities Rating (HQR) Scale and Bedford Workload Scale

Fig 3. ACEL-RATE Simulator Flight Deck

Fig 4. ACEL-RATE Large Field-Of-View Simulator

Table 1. EXAMPLE: LIFT MODES, CONTROL COMMANDS, STICK INCEPTOR MAPPING

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)	Acceleration¹	Vertical Acceleration	Bank Angle	Heading Rate	(0-34 KGS)
STB Lift (15-40 KIAS)		FPA Rate			(34+ KGS)
SWB Lift (30-100 KIAS)	Acceleration²		Roll Rate	Sideslip Angle	
WB Lift (90-120 KIAS)					

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

Understanding Control Inputs and Information Displays

To effectively operate and evaluate approach scenarios using the Integrated Flight Control System (IFCS), pilots must possess a comprehensive understanding of lift principles, control modes, and inceptor functionality. This includes familiarity with inceptor grips, switches, and buttons. Additionally, pilots need to grasp the intricacies of information displays.

1) **Key Display Elements:** The primary flight information displays (as depicted in Figures 5 and 6) play a crucial role. Additional information is presented on the map navigation display and a system health display (not pictured).

These display elements are significant to situational awareness and regulatory compliance and represent a substantial learning task.

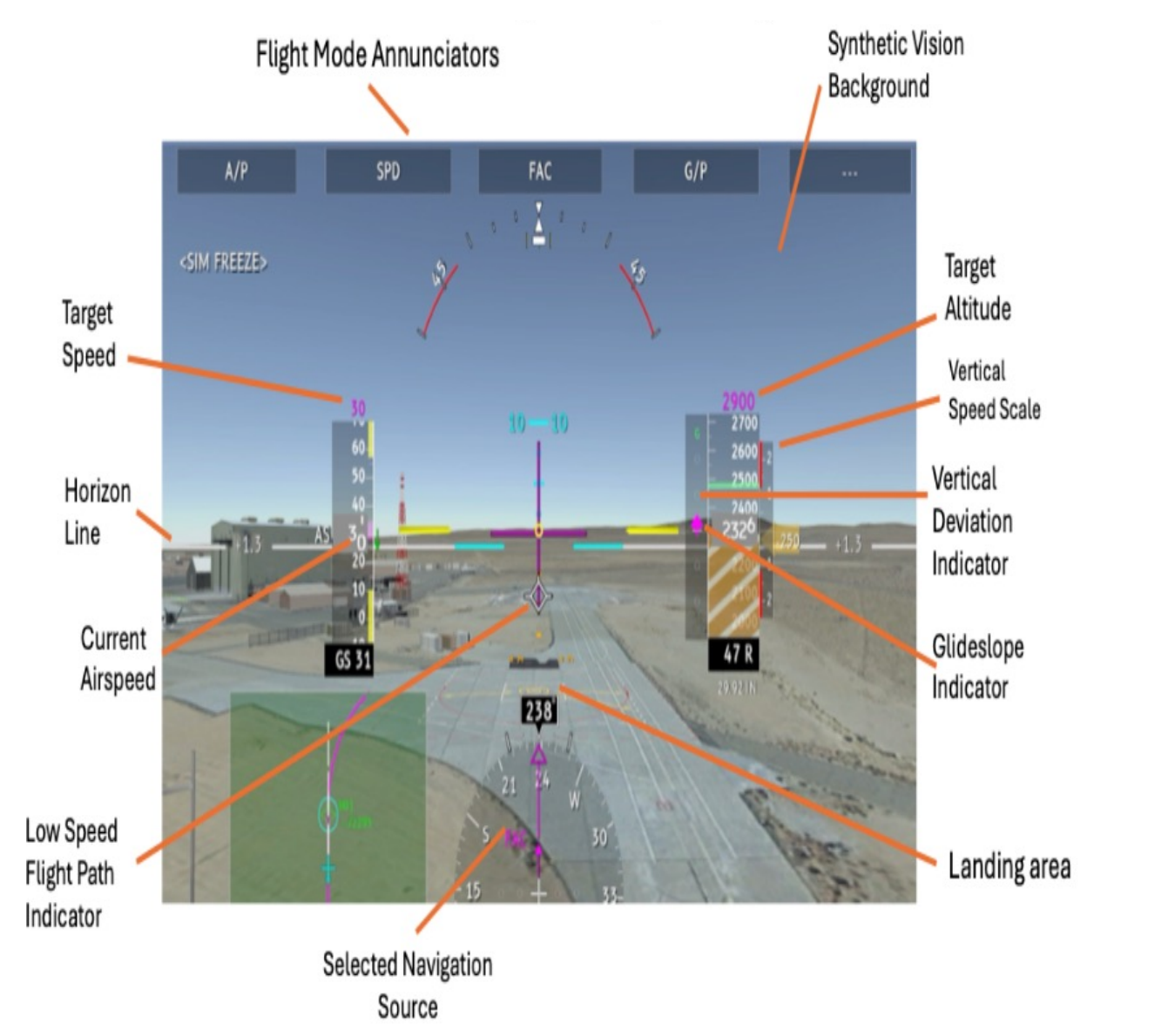


Fig 5. Primary Flight Display

2) Critical Information Elements: During flight scenarios, pilots rely on specific data components, including:

•Flight Director: Essential Path guidance.

•Flight Path Marker Vector: Overlays touch down point and turns green when hover is engaged.

•Predicted Hover Point**:** Essential for precise maneuvering.

•Landing Target: Crucial for safe landings (Nav Display).

•Intruder Aircraft Icons: Shown on the map navigation display for traffic awareness

•Battery Remaining Indication: Monitored via the system health display and used for emphasizing timeliness.

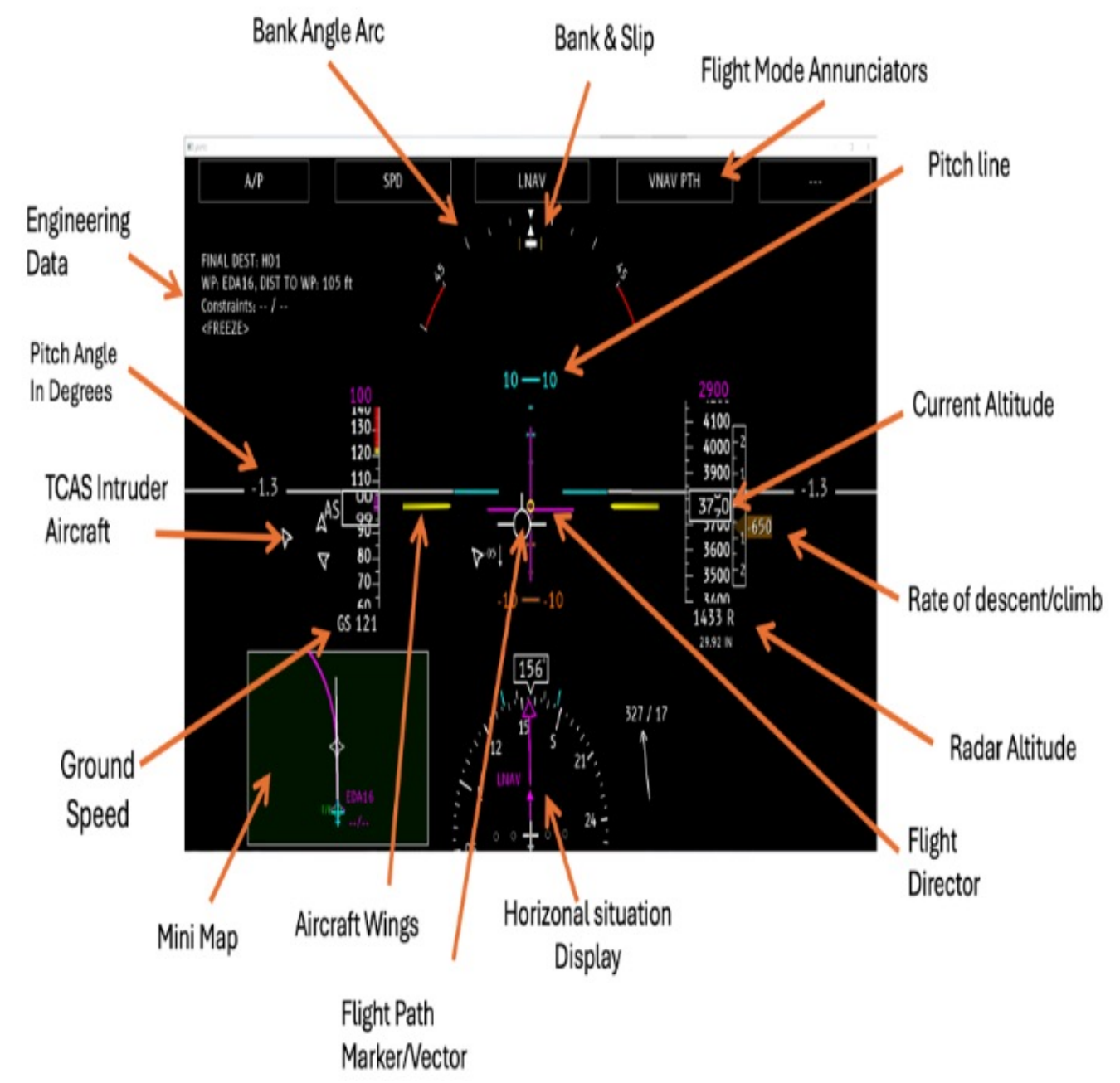


Fig 6. Additional Primary Flight Display Elements

3) Inceptors, Grips, Buttons, and Switches: The inceptors play a central role in aircraft control along with the switches and buttons on the inceptor grips that control auxiliary functions. Again, making this an essential part of the evaluator pilot training.

The left inceptor (Figure 7) is responsible for managing longitudinal thrust, allowing adjustments for forward and aft aircraft movement. It features an auto- zoom button on the left side for map navigation display and permits manual zoom adjustments. The right inceptor (Figure 8) handles lateral and vertical aircraft movement.

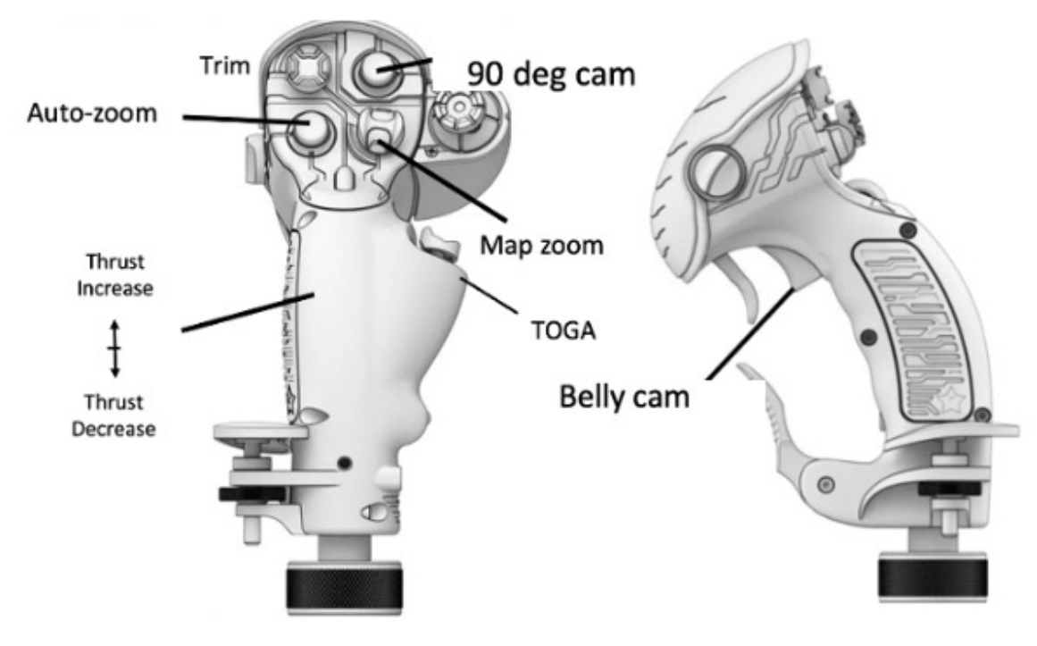


Fig 7. Left stick grips, buttons, and switches

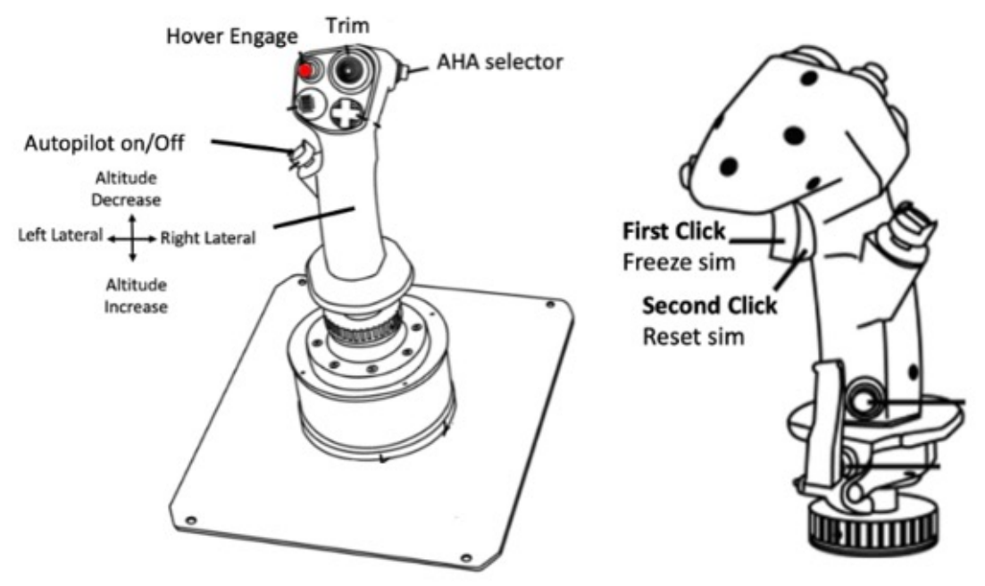


Fig 8. Right stick grips, buttons, and switches

KEY LEARNING CHALLENGES

1. **Novel flight control concept**

- Pilots must suitably master a flight control allocation system where controls are substantially different as airspeed changes.

2. **Efficient transition to hover profiles**

- Despite coming from diverse backgrounds, including possibly never having hovered an aircraft, evaluation pilots must learn how to hover and translate to a landing point.

- The transition from forward flight to hover must optimize energy usage to minimize hover time before landing.

3. **Unique auto flight functions and displays**

- To support efficient transition to hover, vehicle uses three Assisted Hover Automation (AHA) modes.

- AHA modes require pilot activation, monitoring, and control actions to correct for winds and degraded performance.

Subjective rating methods training for the simulation evaluations

Pilots underwent training on the use of two distinct scales: the Cooper-Harper Handling Qualities Rating (HQR) Scale and the Bedford Workload Scale [8][9][10][11][12]. Evaluation pilots with test pilot backgrounds were already acquainted with the HQR scale, while those lacking such experience received instruction and practice on its application. The Bedford workload scale was less familiar to most pilots, requiring training for all evaluation pilots.

Key differences between the scales:

- HQR Scale: Prioritizes performance assessment followed by pilot compensation considerations.

- Bedford Scale: Emphasizes workload assessment first, then a spare capacity evaluation.

Notably, the HQR scale includes an additional decision element, prompting users to assess whether aircraft deficiencies warrant improvement, require improvement, or necessitate mandatory changes. This feature makes the HQR scale less ambiguous in comparison to the Bedford scale in providing recommendations for potential improvements.

Task maneuvers (scenarios) used for evaluation

Once pilots developed basic skills and knowledge for LPC maneuvering, LPC evaluation pilots underwent training in the ACEL-RATE simulator to master maneuver scenarios they would later encounter in the VMS simulator, including diverse environmental and traffic conditions. This preparation involved exposure to environmental situations such as low cloud ceilings and limited visibility. Pilots were encouraged to wear eye tracking glasses to become used to wearing the eye tracker and to formulate their own techniques for executing maneuvers within the established performance criteria.

Overtraining on maneuvers was consciously avoided. Also, wind conditions were intentionally moderated during practice sessions to prevent full acclimatization until the actual scenario AEP-2 trial on the VMS.

Assistive Hover Automation Behavior and Interface:

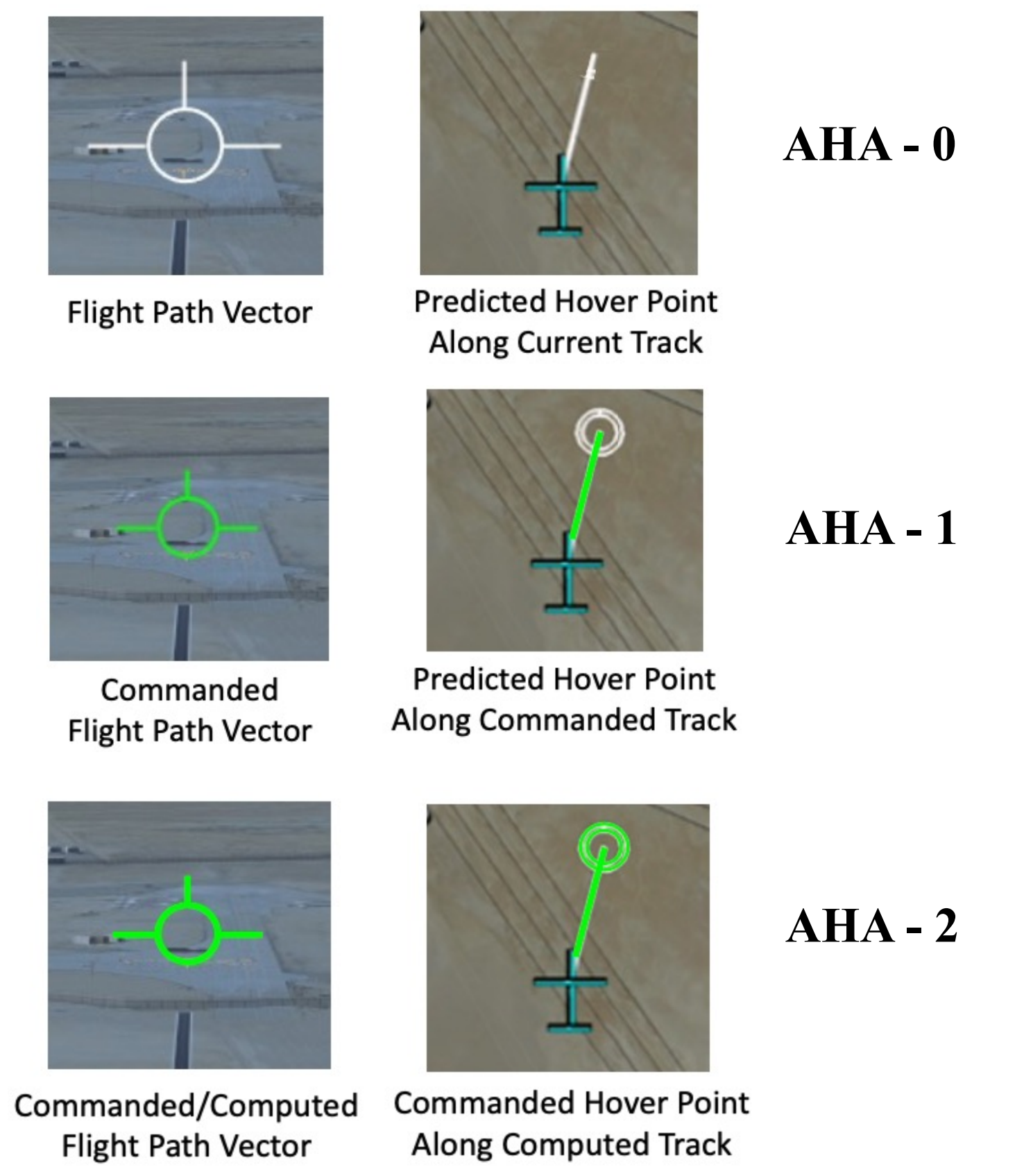
Assistive Hover Automation (AHA - 0)
- Hover Button arms Hover mode
- Predicted hover point is not displayed
- Hover mode engages below 10 kts fwd ground speed
  - Right stick lateral movement transitions from bank angle to lateral ground speed
  - Right stick twist adjusts yaw (pedals in ACEL-RATE)

Assistive Hover Automation (AHA – 1)
- Hover Button engages Transition to Hover
  - Automatically commands a 2.5 knot/sec deceleration rate[1]
  - Automatically commands a decrab maneuver[2]
  - Hover mode engages below 10 kts fwd ground speed
  - Right stick response transitions from bank angle to vector-based track angle

Assistive Hover Automation (AHA – 2)
- Hover Button engaged Transition to a Hover Point:
  - Automatically commands a deceleration to the hover point[1]
  - **Automatically latches to helipad if "close enough" when transition engaged.**
  - Automatically commands a decrab maneuver[2]
  - Hover mode engages below 10 kts fwd ground speed
- Right stick response transitions to command a hover target[3]

(1) Can be modified with left stick inputs.
(2) Can be modified with right stick twist inputs.
(3) Pedal inputs in ACEL-RATE sim. VMS uses right stick twist command.

PFD and NAV Display Assistive Hover Symbologies



IV. CONCLUSION

- The proficiency demonstrated by pilots in mastering new, intricate aircraft designs and unique UAM maneuvers within a single day's training is indicative of the exceptional worth of the training and ACEL-RATE Simulator.
- This rapid learning curve underscores the system's intrinsic value as an instrumental resource in preparatory training activities leading up to critical studies.
- The ACEL- RATE Simulator's expansive field of view, customizable displays and interfaces, and adept and pioneering support team underscore the ACEL-RATE Simulator's significance as an independent asset for future research endeavors.
- The positive reception and high training rating scores from pilots regarding their readiness to execute test scenarios post-training further validates the effectiveness of the instructional methodology employed, given that pilot expertise spanned both fixed-wing and rotary- wing disciplines, it was advantageous that the training instructors possessed diverse aviation experience—affirming that a comprehensive skill set enhances adaptability within this versatile training environment.

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REFERENCES

[1] M. S. Feary, J. T. Kaneshige, T. J. Lombaerts, K. H. Shish, L. A. Haworth, "Evaluation of Novel eVTOL Aircraft Automation Concepts," In proceedings of AIAA Aviation Forum 2023, San Diego, CA, 2023.
[2] Federal Aviation Administration, "Urban Air Mobility and Advanced Air Mobility", https://www.faa.gov/uas/advanced_operations/urban _air_mobility, 2023.
[3] National Aeronautics and Space Administration, "Advanced Air Mobility Project," https://www.nasa.gov/aeroresearch/programs/aosp/ aam, 2023.
[4] 14 CFR Part 1: Aeronautics and Space. (Current through 7/5/24). Text from: Code of Federal Regulations. Accessed 7/6/24.
[5] J. T. Kaneshige, T. J. Lombaerts, K. H. Shish, M. S. Feary, "Command and Control Concepts for a Lift Plus Cruise Electric Vertical Takeoff and Landing Vehicle," AIAA 2023-3910, Session: Control System Design and Simulation, https://doi.org/10.2514/6.2023-3910, 2023.
[6] W. Johnson, C. Silva, E. Solis, "Concept Vehicles for VTOL Air Taxi Operations," AHS Specialists' Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, 2018.
[7] National Aeronautics and Space Administration, "NASA Ames Vertical Motion Simulator (VMS)," https://www.nasa.gov/ames/vms, 2024.
[8] G. E. Cooper, R. P. Harper Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D5153, National Aeronautics and Space Administration, Washington, D.C., April 1969.
[9] United States Army Aviation and Missile Command Aviation Engineering Directorate, "Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft," Technical Report ADS-33E-PRF, https://www.amrdec.army.mil/amrdec/ rdmr-se/tdmd/Documents/ads33front.pdf, 2000.
[10] National Aeronautics and Space Administration, "NASA Spaceflight Human-System Standard," Vol. 2, Revision D, https://www.nasa.gov/wp-content/uploads/2020/10/2022-04-08_nasa- std-3001_vol_2_rev_c_final.pdf, 2022.
[11] National Aeronautics and Space Administration, "Cognitive Workload Assessment Methods," NASA-STD-3001 Technical Brief, OCHMO- TB-032, Rev. C, 2023.
[12] A. H. Roscoe, G. A. Ellis, "A Subjective Rating Scale for Assessing Pilot Workload in Flight: A Decade of Practical Use," Royal Aerospace Establishment Farnborough, UK, March 1990.
[13] Haworth, et al., (2024). "Training the Powered-Lift Evaluation Pilot," 43rd AIAA DATC/IEEE Digital Avionics Systems Conference. October 2024. San Diego, CA.

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