Training the Powered-Lift Evaluation Pilot

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***Abstract*— This paper focuses on the preparation and training of evaluation pilots during the second of two research studies: Automation Enabled Pilot studies 1 and 2 (AEP-1 and AEP-2). These studies are intended to assess novel aircraft automation concepts for electric powered aircraft equipped with Indirect Flight Control Systems (IFCS) capable of Vertical Takeoff and Landing (eVTOL). The AEP-1 study importantly introduced the concept of future evaluation methods used in the AEP-1 study for eVTOL equipped with IFCS that are agnostic and cut cross both airworthiness and operational requirements [1]. The AEP-2 study utilized an updated Lift-Plus-Cruise (LPC) aircraft model and examined pilot interaction with novel procedures and interfaces. Specifically, it explored challenges related to transitioning from forward flight to landing with an industry representative Urban Air Mobility (UAM) approach procedure, establishing baselines for future automation studies [2] [3].**

Keywords—eVTOL, training, pilot, controls, novel, procedures, transitioning, landing, automation, simulation

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 as illustrated in Figure 1 [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.

Fig. 1. eVTOL traffic and vertiports in populated area

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II. eVTOL AIRCRAFT (THE TRAINING COMPLEXITY)

Among the operational complexities, the training of evaluation pilots lies within an interesting array of eVTOL designs. Notably, the Lift-Plus-Cruise (LPC) model, depicted in Figure 2, stands out [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.

Additional LPC unique and complicated key design aspects crucial for the evaluation pilot's awareness, understanding and training of the LPC with IFCS are provided in the following descriptions and figures in this section.

LPC Lift Sources. An illustrative depiction of LPC lift sources are presented in Figure 3. At speeds below 20 Knots Indicated Airspeed (KIAS), the rotors predominantly provide lift. Beyond 20 KIAS, while rotor lift remains dominant, the airframe (wings) begins to influence aerodynamics in the 15-40 KIAS range. At speeds as low as 30 KIAS, lift can shift to become primarily wing borne. Wing borne lift becomes exclusive at 90-120 KIAS, 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 4 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. The inceptor mapping reveals the functional movement and output command of left and right stick inceptors (pilot controls). 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.

Fig. 2. Lift-Plus-Cruise (LPC) Aircraft

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.

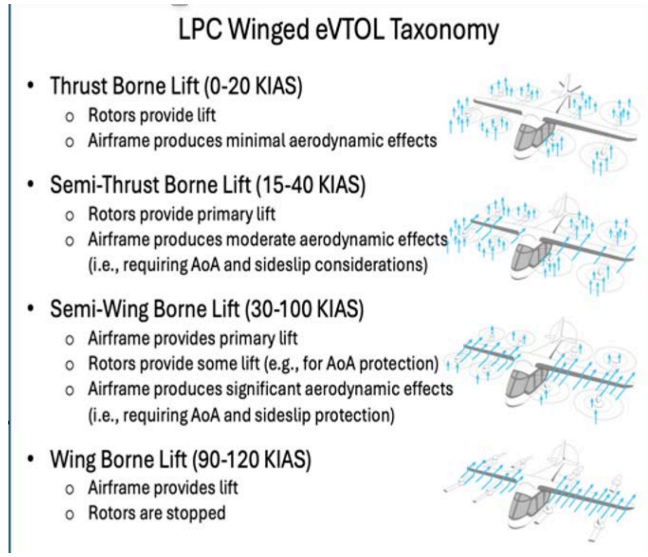


Fig 3. LPC Design Parameters and Lift Sources

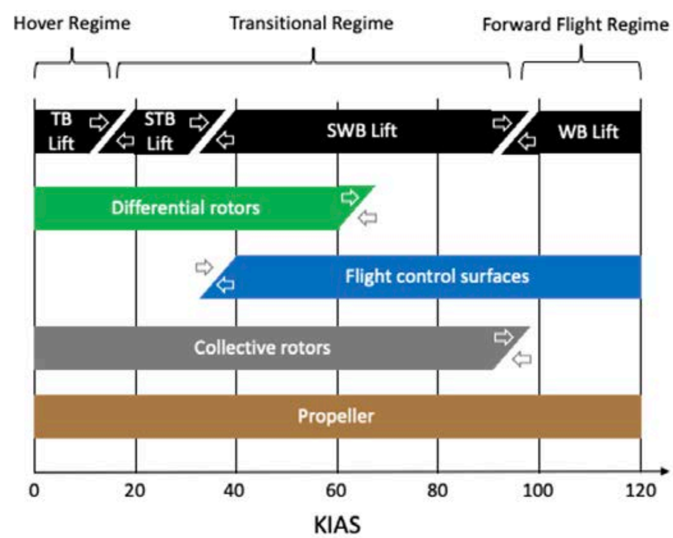


Fig 4. LPC Control Allocation Schedule (Lift Source, Control Surfaces, and Propeller Thrust)

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 Rapid Automation Test Environment ACEL-RATE Simulator shown in Figures 5 and 6. Before arriving at the simulator, each pilot received an Aircraft Flight Manual (AFM) along with other administrative

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)	Acceleration[1]	Vertical Acceleration	Bank Angle	Heading Rate	(0-34 KGS)
STB Lift (15-40 KIAS)		FPA Rate			(34+ KGS)
SWB Lift (30-100 KIAS)	Acceleration[2]		Roll Rate	Sideslip Angle	
WB Lift (90-120 KIAS)					

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

Fig 5. ACEL-RATE Large Field-Of-View Simulator

Fig 6. ACEL-RATE Simulator Flight Deck

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 in-depth 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:

A. *Evaluation Pilot Training Program Outline*

1) *Introduction*

- **Identify Training Challenges:**
    - Consider varied pilot backgrounds and experiences.
    - Address automation concepts, inceptors, and control laws.
    - Allow for differing pilot techniques.

2) Classroom Briefing Material

- **Assessment of Pilot and Trainer Backgrounds:**
  - Understand the knowledge and experience levels of participants
- **Tailoring Presentation:**
  - Customize content based on individual pilot backgrounds.
- **Simulator Description:**
  - Explain simulator displays, controls, and other components.
- **Visual Database and Traffic Descriptions:**
  - Familiarize pilots with visual cues in the simulator environment.
- **Lift and Control Transitions:**
  - Summarize existing slides and materials to enhance pilot awareness.

3) In-Simulator Training and Training Setup

- **Safety Measures:**
  - Discuss safety protocols.
  - Adjust seats and armrests.
  - Optimize pilot field-of-view (lookdown perspective).
  - Understand inceptor movement and switch functions.
- **Visual Environment:**
  - Describe visual database elements (e.g., helipad, traffic).
  - Explore simulator field-of-view, sky ceiling, and visibility conditions.

4) Preliminary Maneuver Training: Low-Speed Flight

- **Objective:**
  - Teach pilots how to maneuver to the center of the helipad.
  - Address differences in control laws with hover engaged and not engaged.
- **Hover Function:**
  - Explain hover function and its impact on control.
  - Identify each control law and its envelope limits.
- **Limited Free Play:**
  - Allow practice within low-speed flight parameters.

5) Preliminary Maneuver Training: Up and Away Flight

- **Objective:**
  - Identify lift modes and control changes based on airspeed.
  - Experience transitions across control axes.
  - Transition between low-speed and higher-speed regimes.
- **Limited Free Play**
  - Explore full speed range maneuvers.

B. Understanding of Inceptor Systems 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 7 and 8) play a crucial role. Furthermore, Figure 9 illustrates the map navigation display, while Figure 10 showcases the system health display. These internal display elements are significant to situational awareness and regulatory compliance.

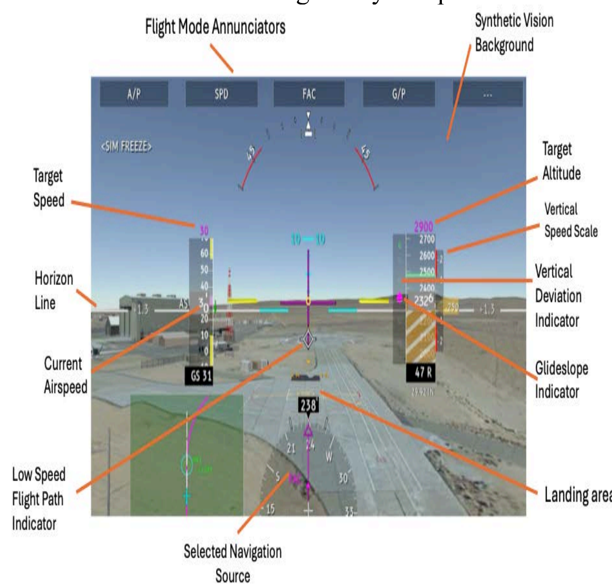


Fig. 7. Primary Flight Display with Synthetic Background

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.
- **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.

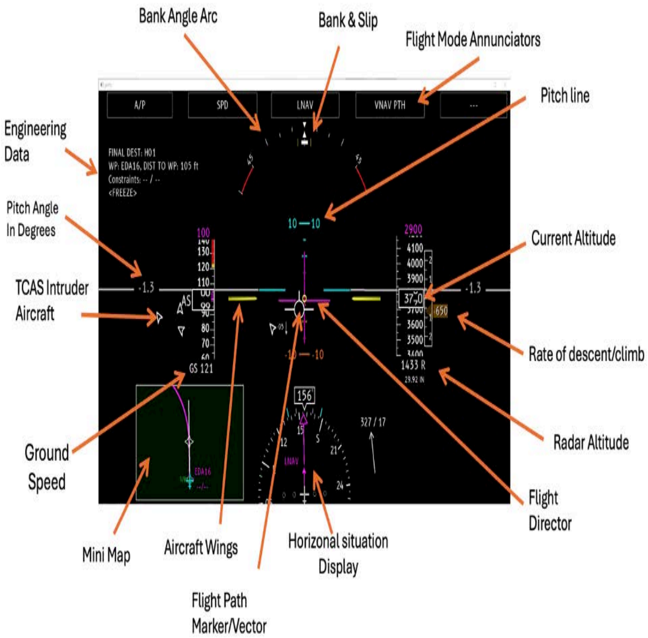


Fig. 8. Primary Flight Presenting Addition Information Elements (The black background is for illustration only)

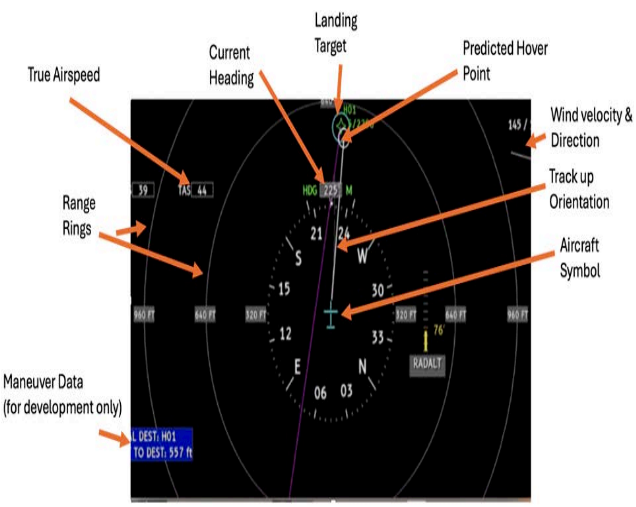


Fig. 9. Map/Navigation Display

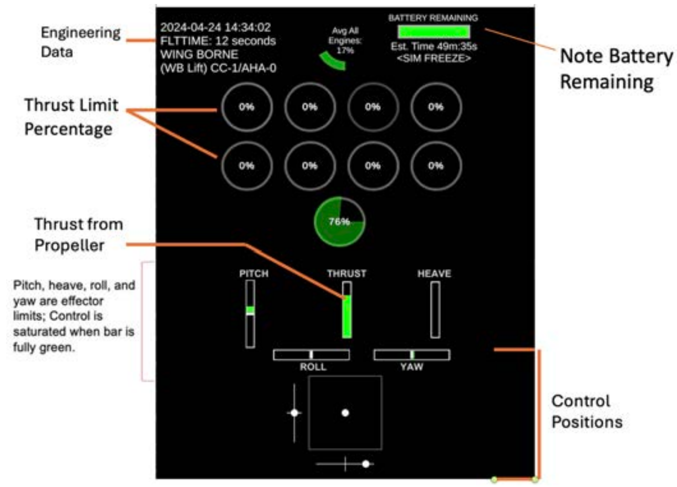


Fig. 10. System Health Display

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 11) 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 12) handles lateral and vertical aircraft movement. Pedals are provided on the ACEL-RATE Simulator for yaw control. While the ACEL-RATE Simulator used pedals (Figure 13) for yaw control the VMS integrated yaw control directly into the right inceptor, eliminating the need for pedals. Camera controls include a belly camera (activated by a trigger-like switch under the right inceptor) and a 90-degree look-down camera (selected via a button on the left inceptor). Both cameras temporarily replace the map navigation display. Lastly, the TOGA (Take Off Go Around) switch on the left inceptor aids pilots in avoiding traffic during the final approach, while the hover engage button serves as an arming or engage button based on flight phase or automation scenarios.

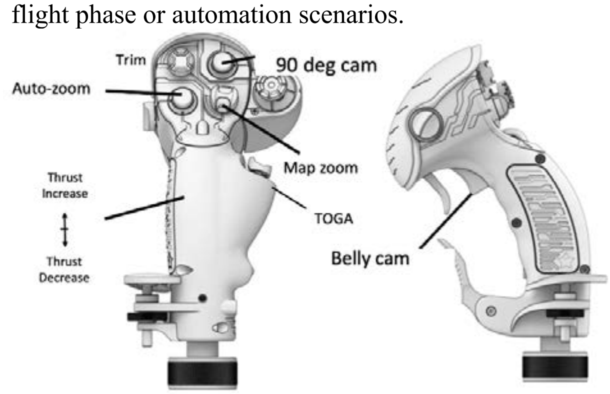


Fig. 11. Inceptors, grips, buttons and switches (Front and Side Views)

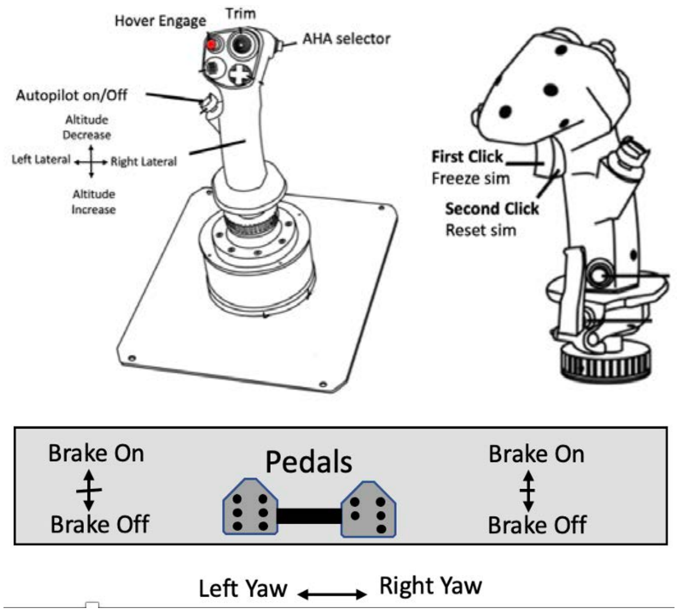


Fig. 12. Right Inceptor (front and back view) and Pedals

C. 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 (depicted in Figure 13) and the Bedford Workload Scale (shown in Figure 14) [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.

D. Task maneuvers (scenarios) used for evaluation

Once pilots developed basic skills and knowledge for LPC maneuvering, LPC evaluation pilots underwent training in the ASR 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.

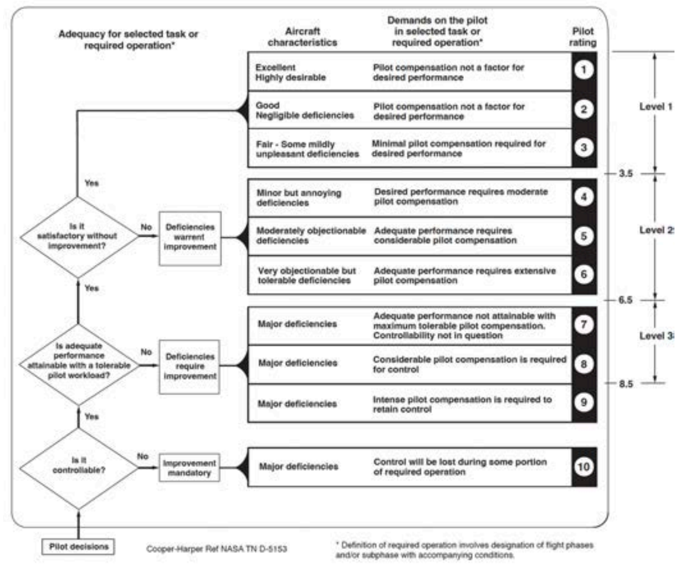
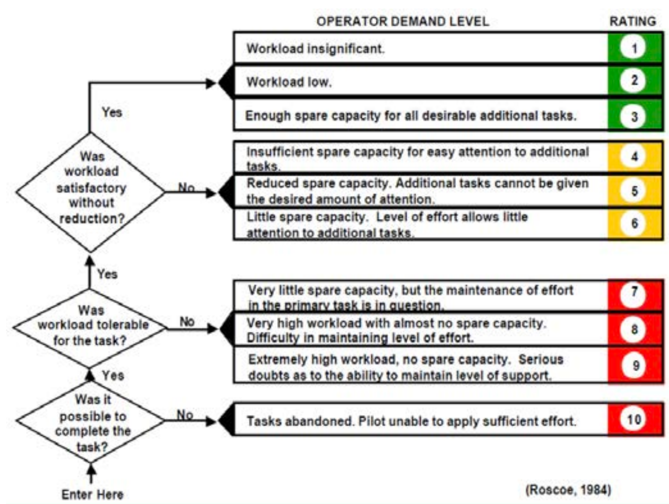


Fig. 13. Cooper-Harper Handling Qualities Rating (HQR) Scale



engine

Fig. 14. Bedford Workload Scale

Pilots also received instructions and performance requirements for landing on helipads—specifically aiming for center of the helipad during landings. Varied LPC approaches were observed; some pilots preferred terminating to the ground while others opted for an initial hover before setting down near or on the helipad's center. A component of this training was the utilization of battery status indications on health displays to signal low battery conditions, thereby heightening pilot awareness for timely landings. The landing of the aircraft marked the completion of approach maneuvers.

The following task maneuvers were flown by the pilots during practice and later for data collection on the VMS. The approach procedure shown in Figure 15 started at 0.4 nautical miles prior to EDA16 as illustrated on the approach and ended in a 6-degree approach to the helipad. Other maneuvers were 6- and 12-degree approaches made from the final course intercept and 6-degree approaches from final. An illustration of the final approach profile is provided in Figure 16.

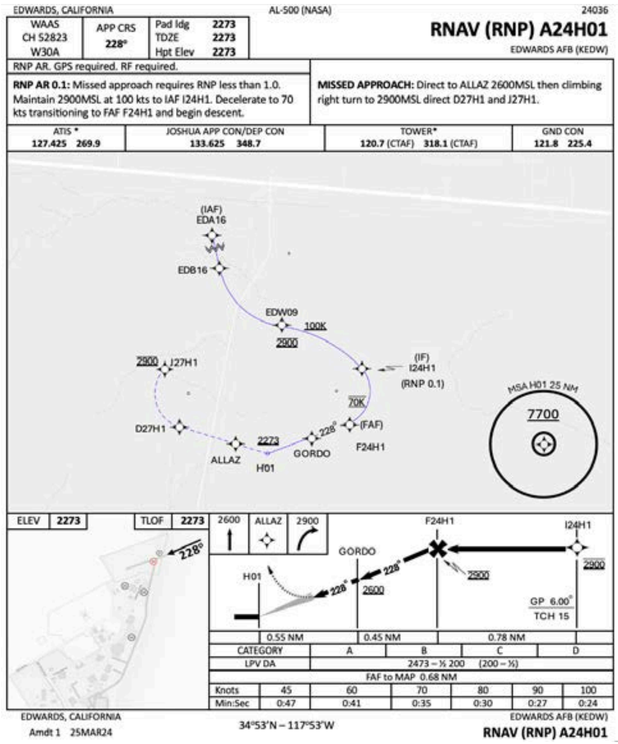


Fig. 15. Approach plate for the RNAV (RNP) 6 degree approach

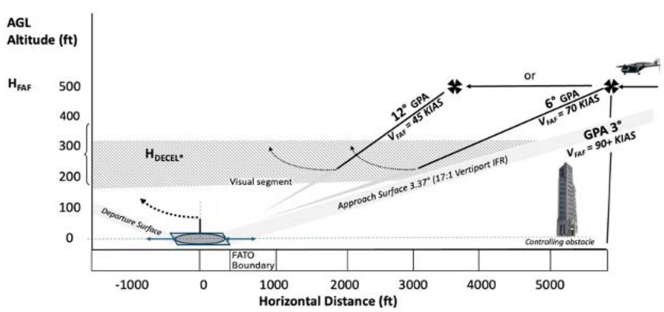


Fig. 16. Profile view of 6- and 12- degree approaches

The study scenarios necessitated pilots to employ three distinct automation methods, as outlined in Figure 17, for decelerating the LPC aircraft during approach and accurately positioning it on the helipad's center. The first method, Assistive Hover Automation (AHA-0), required manual deceleration during approach and precise manual positioning for landing. In contrast, AHA-1 automatically commanded a deceleration rate of 2.5 knots per second, along with other automation assists depicted in Figure 17. AHA-2 facilitated automatic deceleration to a hover point.

Pilots determined when to engage the hover button for AHA-1 and AHA-2 by timing the engagement (pressing the right inceptor's hover button) when the predicted hover point symbol (circle) overlaid the circle representing the intended hover area or point. Following a successful engagement, the LPC automatically decelerated toward the target area or position.

Pilots encountered additional challenges when using the AHA-0 automation version compared to AHA-1 and AHA-2. In the former, pilots often attempted to maintain sufficient speed to stay on the wing, conserving battery energy until executing a last-moment final flare and touchdown. This approach was colloquially referred to as the 'bird-on-the-wire' method. Landing accuracy was difficult to achieve.

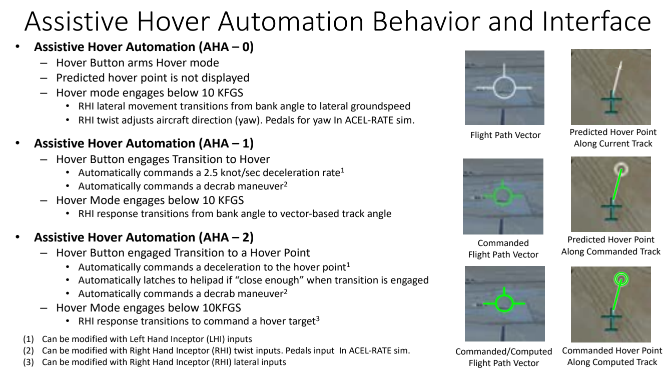


Fig. 17. Assistive Hover Automation (AHA) Concepts

After completing training on the ACEL-RATE Simulator, instructors and evaluation pilots conducted a debriefing session with the pilots. The pilot debriefs covered the following areas:

1. **Pilot Observations:** Pilots shared their insights and experiences from the training exercises.
2. **Observer Observations:** External observers provided feedback on pilot performance.
3. **Maneuver Comprehension:** Ensuring that all pilots understood each maneuver and how to execute it effectively.
4. **Control Function Awareness:** Discussing pilots' familiarity with various switches and controls in the aircraft cockpit.
5. **Display Modes (Flight Handling Application):** Reviewing different display modes, particularly those related to flight handling and approach applications.
6. **System Health Display:** Examining the battery energy as displayed on the monitor.

The pilot debrief above was followed by a briefing on the VMS shown in Figures 18, 19 and 20 to discuss what to expect and differences between the simulators and the operation of the VMS motion-based simulator. The VMS essentially replicated the displays and outside visuals. The differences were primary the large motion base and the three-axis right inceptor that includes the yaw on the inceptor. Other differences were the pilot procedures for operating the motion base, the FOV, the seat, arm rests and the left inceptor grip and button locations on

Fig. 18. VMS Cab

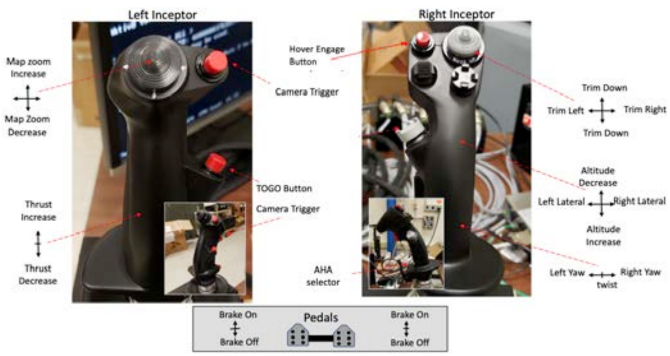


Fig. 19. VMS inceptor controls, grips, and mapping

the grip. The back seat of the VMS was occupied with a researcher involved with collecting eye tracking data and other observations. Interestingly, the pilot flying sometimes mentioned the ride comfort of the researcher in the jump seat thus adding another dimension to the simulation that was not planned.

IV. Conclusion

The proficiency demonstrated by pilots in mastering new, intricate aircraft designs and unique UAM maneuvers within a single day's training on the VMS 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. Furthermore, ACEL-RATE Simulator attributes such as an expansive field of view, customizable displays and interfaces, coupled with the provision of an 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.

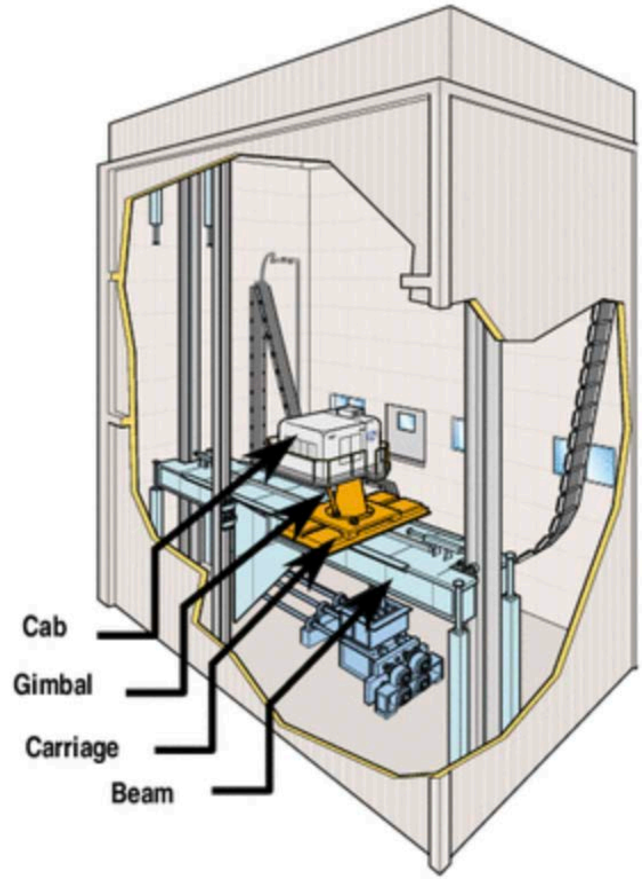


Fig. 20. NASA-Ames Vertical Motion Flight Simulator (World's largest Motion Base)

Acknowledgment

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