An Examination of Powered-Lift Aircraft Operations in Urban Areas

Michael Feary
Human-Systems Integration Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
michael.s.feary@nasa.gov

John Kaneshige
Intelligent Systems Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
john.t.kaneshige@nasa.gov

Kimberlee Shish
Intelligent Systems Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
kimberlee.h.shish@nasa.gov

Amber Villa
Human-Systems Integration Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
amber.n.villa@nasa.gov

Loran Haworth
Human-Systems Integration Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
loran.a.haworth@nasa.gov

Thomas Lombaerts
Intelligent Systems Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
thomas.lombaerts@nasa.gov

Kevin Monk
Human-Systems Integration Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
kevin.j.monk@nasa.gov

Nelson Iwai
Human-Systems Integration Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
nelson.iwai@nasa.gov

John Archdeacon
Human-Systems Integration Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
john.archdeacon@nasa.gov

Mieczyslaw Steglinski
Intelligent Systems Division
National Aeronautics and Space Administration
Moffett Field, CA, USA
john.archdeacon@nasa.gov

***Abstract*—The development of distributed electric propulsion has enabled many novel Powered-Lift aircraft concepts, referred to electric Vertical Takeoff and Landing (eVTOL) aircraft. This paper describes the development of a study focused on addressing the need for evaluation methods that effectively evaluate novel aircraft automation concepts independent of aircraft configuration. The research specifically focuses on evaluation of novel aircraft concepts with Indirect Flight Control Systems that are capable of Vertical Takeoff and Landing. The research activity consists of development of industry representative aircraft, aircraft automation, training, and procedural development as well as data collected in studies, referred to as Automation Enabled Pilot studies 1 and 2 (AEP-1 and AEP -2). The AEP-1 study focused on investigating methods of evaluation of various methods of aircraft control and the effects of levels of automation and environmental effects on those transitions. This paper describes the development of the AEP-2 study and implications for the operation of eVTOL Powered-Lift aircraft.**

Keywords—Human-Automation Interaction, Powered-Lift, eVTOL, UAM

I. Introduction

The development of distributed electric propulsion has enabled many novel Powered-Lift aircraft concepts, referred to electric Vertical Takeoff and Landing (eVTOL) aircraft. This paper describes a research activity focused on addressing the need for evaluation methods that effectively evaluate novel aircraft automation concepts independent of aircraft configuration. The eVTOL aircraft industry has proposed many novel aircraft, automation, pilot interface and operational concepts. The research specifically focuses on evaluation of novel aircraft concepts with Indirect Flight Control Systems that are capable of Vertical Takeoff and Landing. The research activity consists of development of industry representative aircraft, aircraft automation, training, and procedural development as well as data collected in studies, referred to as Automation Enabled Pilot studies 1 and 2 (AEP-1 and AEP -2). The results of the studies are intended to provide a reference for the Advanced Air Mobility aircraft industry and regulators for evaluation of the aircraft, operational procedures, and pilot requirements.

The AEP-1 study focused on investigating methods of evaluation of various methods of aircraft control, and the effects of levels of automation and environmental conditions on those transitions. The evaluation method under investigation is based on Aeronautical Design Standard 33 (ADS33E-PRF) methodology [1] for evaluating civil Vertical Takeoff and Landing (VTOL) aircraft. ADS-33 was developed by the U.S. military for assessing handling qualities of VTOL capable aircraft. A key component of the method is the description of mission tasks and associated performance criteria. While the method was developed to assess handling qualities of Vertical Takeoff and Landing aircraft, the method has also been extended for use in evaluation of remotely piloted aircraft. An objective for the Automation Enabled Pilot Studies is to examine the use of the method in evaluation of civil aircraft with increasingly

This work is supported by the NASA Air Mobility Pathfinder (AMP project.

automated systems. The study used three demonstration maneuvers, the decelerating approach, precision hover and rejected takeoff to identify potential handling deficiencies associated with different flight control methods. The study demonstrated that the evaluation method was useful for evaluation of industry representative models of eVTOL aircraft with varying levels of automation. While the results of AEP-1 have been described in a previous paper [2], this paper will discuss the highlights of the results and implications for the industry as an introduction to the second study. The paper will describe a framework for categorizing levels of Pilot-Automation Interaction for control automation.

This paper describes the development of the AEP-2 study and some initial findings from the development of the aircraft automation and procedure development. In AEP-2 representative concepts were selected to examine the impact of pilot interface changes that are currently without regulatory guidance on performance of representative eVTOL approach tasks.

AEP-2 used an updated Lift Plus Cruise aircraft model and a subset of the novel aircraft automation to examine pilot interaction for using proposed descent and approach procedures that could be used for Urban Air Mobility [2][3][4][5]. The AEP-2 study examined demonstration maneuvers, and pilot interfaces that are representative of industry concepts for eVTOL aircraft conducting proposed Urban Air Mobility operational concepts. The focus of the study was the evaluation of pilot use of novel automated functions and predictive displays for Vertical Takeoff and Landing operations.

The paper will discuss the development effort to define the scope of the approach and landing tasks and implications for evaluation of proposed Advanced Air Mobility aircraft concepts. The development effort included an examination of pilot requirements (including cognitive, skill, attention, and alertness requirements) for conducting operationally representative maneuvers with a representative aircraft.

Due to delays in the start of the study, data collection was not completed until the end of June 2024 and subsequent analysis is not yet complete. This paper will discuss the development, a few high-level discoveries, and implications for future work.

II. AEP-2 METHOD

The AEP-2 study investigated flight performance and pilot workload throughout the UAM approach maneuver under varying automation configurations and environmental conditions.

A. *Materials*

1) Simulation Environment

The simulation environment, including aircraft and automation integration, cockpit interfaces, out-the-window visuals, traffic, and weather were developed in the Aerospace Cognitive Engineering Laboratory - Rapid Automation Test Environment (ACEL-RATE) fixed base simulator. ACEL-RATE was also used for training participants prior to the data collection runs using the NASA Vertical Motion Simulator (VMS). The cockpit configurations for ACEL-RATE (Fig. 1) and the VMS (Fig. 2) are illustrated below.

Fig. 1. ACEL-RATE Pilot Station

Fig. 2. VMS Pilot Station

2) AEP-2 Lift PlusCruise Aircraft

A 6000-pound, Lift Plus Cruise (LPC) Powered-Lift aircraft configuration (illustrated in Fig. 3) was used for AEP-2. The aircraft was an updated version of the LPC aircraft model used in previous studies [6][7], with modification to provide collective control to the vertical propulsion units and a beta range to the pusher propeller.

Fig. 3. Lift Plus Cruise Aircraft

B. Participants

The AEP-1 study utilized formally trained test pilots as participants to evaluate handling qualities of the novel control systems and interfaces, however, AEP-2 aimed to begin to evaluate the interfaces in an environment more closely associated with operations and sought to increase the diversity of participant background to solicit feedback on candidate operational procedures. Currently there are no civil operational eVTOL operational pilots or approved eVTOL pilot training programs. The participants for the study were selected for having a current role evaluating eVTOL aircraft airworthiness, training, and qualification requirements, which enabled feedback on the validity of the aircraft, automation, interface, and procedure concepts.

Eleven pilots participated in the study, eight of whom were employed by government regulators and three participants representing eVTOL aircraft companies. All participants were qualified airplane pilots, and eight participants had helicopter flight experience. All pilots had experience with eVTOL aircraft characteristics, and eight participants were qualified to fly both fixed wing and helicopters.

C. AEP-2 Aircraft Automation

Previous research efforts [2][7] examined different industry representative command concepts and inceptor configurations. Across these conditions, the studies identified controllability challenges while transitioning to hover and landing. This led to the development of "Hover Mode" to aid controllability and reduce pilot workload [7][8]. "Hover Mode" engages when the aircraft has less than 10 knots of forward groundspeed and enables the pilot to command groundspeed or a target hover point rather than commanding acceleration. AEP-2 examined different levels of hover prediction and assistance, referred to as Assistive Hover Automation (AHA) levels, specifically focusing on pilot assistance for the three lower automation levels (AHA-0, AHA-1, and AHA-2) and interfaces to support the transition from a constant speed decelerating approach to a vertical landing.

1) Pilot – Automation Interaction (PAI) Framework

Previous research efforts sponsored by the FAA and NASA led to the development of industry representative command concepts for aircraft with Indirect Flight Control Systems (IFCS) [7] and a reference framework referred to as the Pilot-Automation Interaction (PAI) framework. The lowest four levels of the PAI framework describe individual levels of aircraft control with supporting automation, while aircraft control is mostly automated for the upper four levels. AEP-1 examined representations of control automation levels from and different inceptor configurations with pilot interfaces held constant [2]. Using the PAI framework, AEP-2 examined different Hover Assistance (AHA) functions and interface changes with control concepts held constant. The AEP-2 AHA function focus areas are illustrated in Fig. 4.

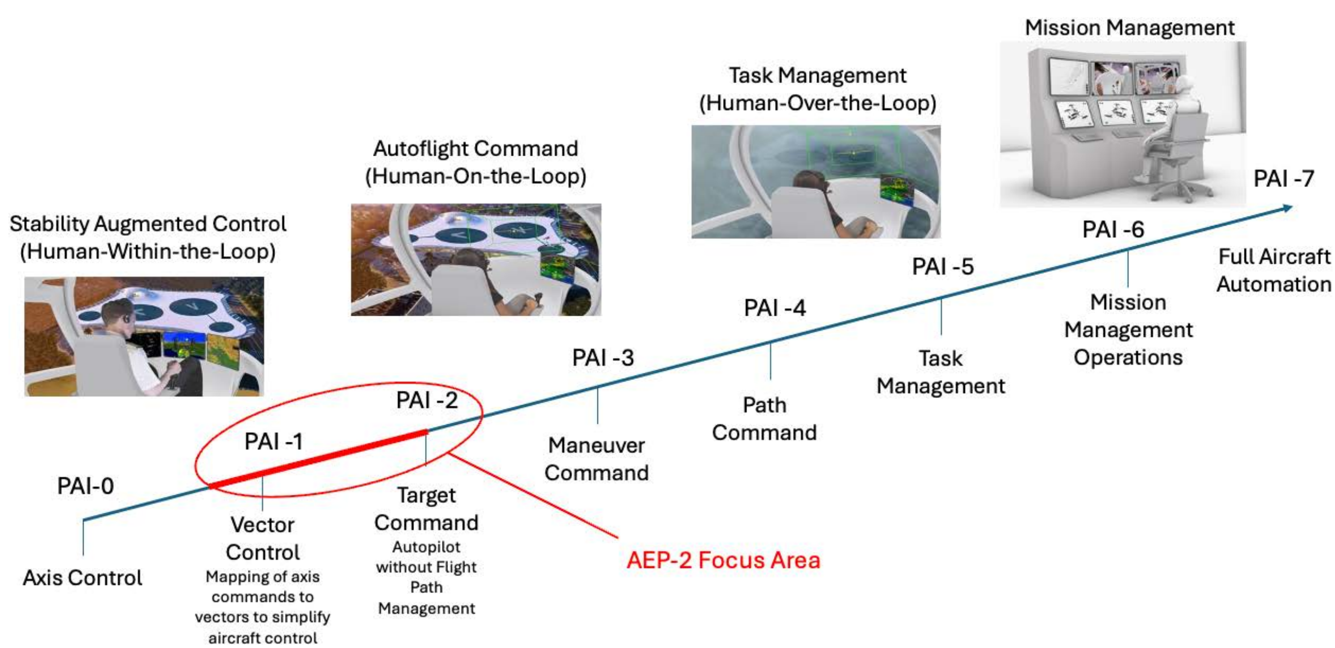

Fig. 4. Pilot-Automation Interaction Framework highlighting AEP-2 investigation area (in red)

2) Assistive Hover Automation and Interface

The lowest level assistive automation function is referred as AHA-0. "Hover Mode" can be armed at any time in AHA-0 and will automatically engage when the aircraft drops below 10 knots Forward Groundspeed (KFGS). When Hover Mode engages it will aid the pilot by holding altitude and direction and return to 0 knots groundspeed when the pilot is not providing inputs. Since the aircraft is attempting to maintain airmass referenced values, hover mode will aid the pilot by correcting for steady state wind conditions, but wind gusts will cause the aircraft to drift while the automation attempts to return the groundspeed to 0. AHA-0 provides a leader line on the map display to show predicted track information.

AHA-1 adds to AHA-0 functionality by initiating an automated deceleration at 2.5 knots per second when Hover Mode is armed and displays a prediction of the hover point at the end of the deceleration. In AHA-1 the predicted hover point is airmass referenced which makes the accuracy of the predictions subject to changes in wind conditions. Additionally, AHA-1 will automatically transition from a crab to sideslip wind correction as the aircraft slows. The pilot will still be required to make corrections to the aircraft trajectory if the predictions are incorrect and will drift in hover if there are gusts.

AHA-2 is designed to further reduce workload. Like AHA-1, AHA-2 allows the pilot to designate a target hover point and start an automated deceleration at 2.5 knots per second. In AHA-2, the hover point is earth-referenced (i.e., latitude and longitude) and the auto flight system adjusts the deceleration rate to arrive at the designated hover point. For the AEP-2 study, the designated hover point will also "latch" to a waypoint that is near the hover point target to reduce workload in the initiation of the deceleration.

Pilot inputs will alter the predicted or target hover position before or after the deceleration has started in both AHA-1 and AHA-2. Fig. 5 summarizes the pilot interface and behavior differences across AHA-0, -1 and -2.

The command concepts were also restricted but did vary across AHA condition to match the changes in the pilot interface and assistance levels (i.e., controlling a hover target rather than using a predicted hover point). The differences in command concepts across AHA-0, AHA-1 and AHA-2 are shown in Fig.5.

D. AEP-2 Pilot Displays

The cockpit displays were designed to provide industry representative information elements. The displays were held constant across all conditions with the exceptions associated with the AHA conditions described below. Participants were provided with a Primary Flight Display (PFD), Navigation Display (ND) and Systems Display (SD).

The PFD included camera based Enhanced Vision, an inset map, a dual cue Flight Director, Horizontal Situation Indicator, indications for the approach course, speed, altitude and heading target and Flight Path Vector indications as shown in the left column of display elements in Fig. 5 in addition to basic PFD display elements.

The ND was industry representative for transport category aircraft without displays of terrain or airspace boundaries but did provide symbology for traffic. The flight plan route for the approach was shown on the ND as well as the AHA hover display elements (Fig. 5). The hover point display element is shown on the ND in Fig. 6.

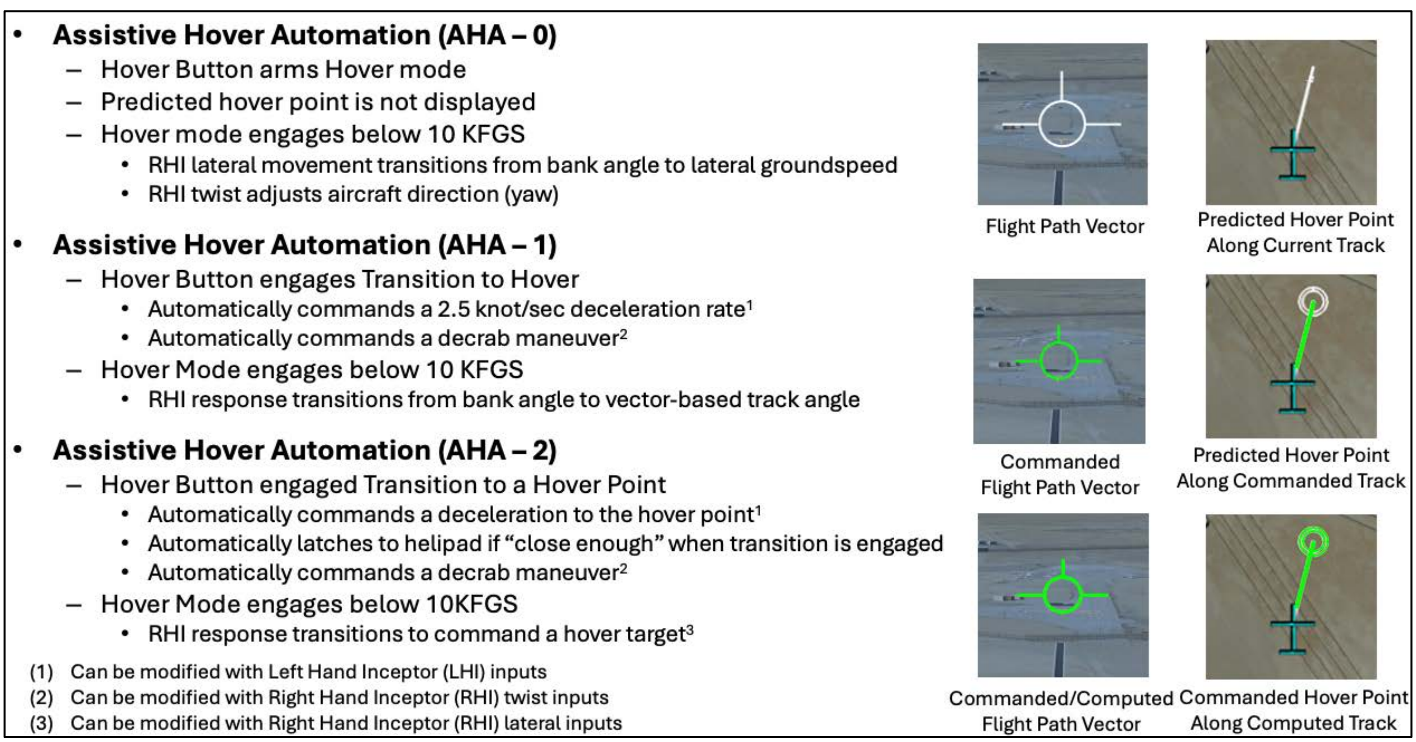

Fig. 5. Comparison of pilot interface concepts and AHA behavior differences across AHA-0, -1 and -2

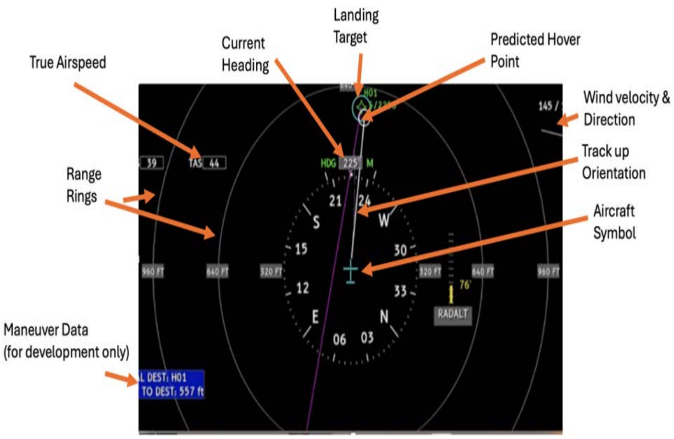

Fig. 6. AEP-2 Navigation Display

The Systems Display provides information on power output and limits for individual propulsors, position and limits for inceptor and effectors and battery state as well as test information showing the current AHA condition. Of the information displayed, the battery display and information about the AHA state were the most useful information elements for the AEP-2 study. The battery display presented State of Charge, which was used as a proxy for the time performance criteria for the task.

E. *AEP-2 Inceptor Configuration*

In comparison to AEP-1, which held the pilot interfaces constant and varied the command concepts and inceptor configurations, AEP-2 varied the pilot interfaces but restricted differences between command concepts and inceptor configurations.

The inceptor configurations did vary between training in ACEL-RATE and data collection in the VMS. ACEL-RATE used a 2 + 1 + 1 inceptor configuration (Fig. 7), in which the Right-Hand Inceptor (RHI) commands vertical rate, roll rate or lateral translation, the Left-Hand Inceptor (LHI) commands longitudinal velocity and the rudder pedals command direction. The VMS used a 3 +1 inceptor configuration, exchanging rudder pedals for twist on the right inceptor to command direction (Fig. 8).

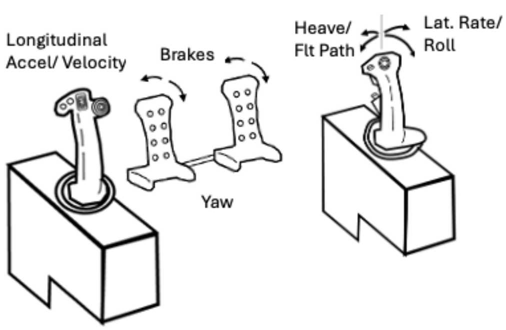

Fig. 7. ACEL-RATE 2 + 1 + 1 inceptor configuration

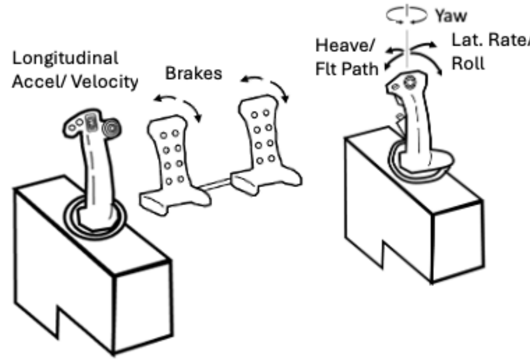

Fig. 8. VMS 3 + 1 Inceptor Configuration

F. *Candidate Urban Air Mobility Approach Procedure Development*

An initial step for AEP-2 was to develop approach procedures representative of those needed for Urban Air Mobility (UAM). The FAA UAM V2 Concept of Operations [3] defines corridors with lateral and vertical dimensions to satisfy the navigation precision required for high-capacity operations in complex urban airspace. Using these definitions, a baseline assumption is that instrument approach procedures will be required to meet the UAM navigation precision requirements, regardless of weather conditions. The AEP-2 team used a combination of existing instrument approach procedure and vertiport specification [4][9][10] elements to construct an example approach procedure for the AEP-2 study maneuvers.

The AEP-2 approach procedures assumed a need for descending, decelerating, and turning elements to navigate the complex urban airspace. RNP-AR approach procedures [4] were used as a baseline for the initial and intermediate segments of the AEP-2 approach procedure as an approved instrument procedure that allows use of a Radius-to-Fix (RF) leg. The navigation precision for the AEP-2 approach was modified to RNP 0.1 to align the low altitude and high-density operations assumptions for UAM and to provide a performance baseline for the evaluation.

The final approach segment of the approach consisted of a descending constant airspeed segment until reaching a deceleration height (H_{decel}) followed by a deceleration to a vertical landing. The constant airspeed segment used an airspeed derived from an assumption of a descent rate of less than 1000 feet per minute based on previous work by Webber [11]. Two approaches were constructed for AEP-2, with a nominal (6-degree) approach using a 70-knot airspeed and a steep (12-degree) approach using a 45-knot airspeed for the constant speed segments. Fig. 9 shows the profile and speeds for both the 6-degree and 12-degree approaches. Fig. 10 shows the approach plate used for the 6-degree approach.

The deceleration segment was designed for a rate of 2.5 knots per second deceleration in no wind conditions. This deceleration rate is aggressive when compared to current nominal VTOL operations but assumes a desire to remain at a higher speed for as long as practical to reduce energy consumption, noise footprint and improve diversion options.

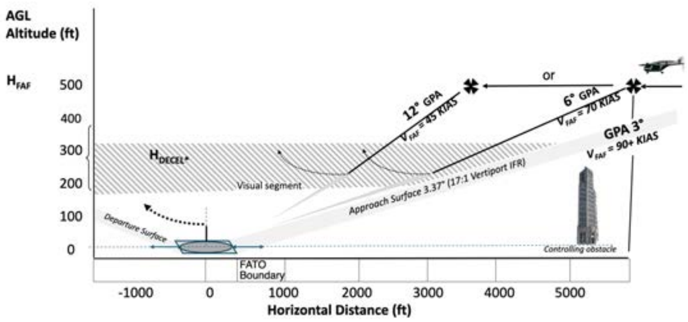

Fig. 9. AEP-2 Normal and Steep Approach profiles

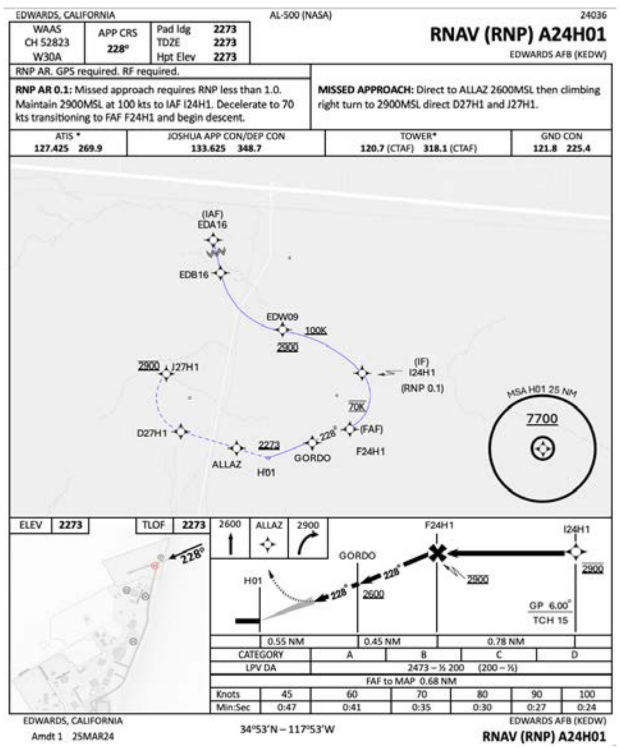

Fig. 10. AEP-2 Approach Chart (6-degree)

III. Study Procedure

The AEP-2 study consisted of four phases: pre-study preparation, on-site training, data collection and post-study feedback

A. *Pre-study preparation*

Prior to arriving onsite for the study, all participants were sent a description of the study as well as a preparation document referred to as an Aircraft Flight Manual (AFM). The AFM described the Lift Plus Cruise aircraft model characteristics, pilot interfaces, command concepts and some procedure descriptions. However, unlike conventional AFMs, some performance and procedure information was missing due to the immaturity of the aircraft model and some additional information regarding Powered-Lift concepts and descriptions of the ACEL-RATE and VMS simulators was included.

B. *On-site Training*

Onsite training consisted of a briefing describing the objective of the study, the schedule, and a review of the aircraft, automation and tasks under investigation. This was followed by training in the ACEL-RATE simulator (Fig.1). Training included a review of aircraft behavior and performance and demonstrations of the approach procedure in different environmental and automation conditions. If needed, participants were provided instruction on the Cooper-Harper Handling Quality Rating scale and the Bedford Workload Scale. Participants were also tested the fit and vision correction for the eye tracking glasses. At the end of the training participants received a survey asking questions about the different aspects of the aircraft, automation and tasks and whether they felt they were prepared or had any questions about the data collection day. The training is described in more detail in [12].

The participants moved to the Vertical Motion Simulator (VMS) at NASA Ames Research Center (Fig. 2) for the second day. Participants were briefed on the protocols for the VMS operation before conducting a 30-minute familiarization session in the VMS while on motion prior to starting the first data collection session. Participants were allowed to fly the approach procedure in different wind conditions, and could extend the familiarization session if needed, but were not allowed to repeatedly practice the test tasks. Participants were asked to confirm when they were ready before the beginning of data collection.

C. *Data Collection*

1) *Independent Variables*

The Independent Variables for the study included the three previously described automation conditions, five wind, three ceiling and visibility conditions, and a secondary task of avoiding traffic conflicts.

a) *Automation Conditions*

The three Assistive Hover Automation conditions (AHA-0, AHA-1, AHA-2) were used as the primary independent variable.

b) *Wind Conditions*

The wind conditions were chosen based on the performance of the LPC aircraft. Four wind conditions were used in the study. Calm winds, 17kt Quartering Headwind, 10kt Quartering Tailwind, or 17 kt crosswind. The wind magnitudes also agree with current Draft FAA Advisory Circular for Type Certification of Powered Lift Aircraft [13].

c) *Visibility and Ceiling*

eVTOL aircraft are expected to be certified for Visual Flight Rules (VFR) initially, however current day VFR operational rules for helicopters allow operation in visibility as low as ½ statute mile clear of clouds and airplanes are allowed to operate in visibilities as low as 1 statute mile clear of clouds [14]. This provided a basis for examining two different environments, Good Visual Conditions (Clear and Visibility Unlimited), Degraded Visual Conditions (1 statute mile visibility in mist).

Additionally, while IFR operations are not expected for initial operations, Instrument Meteorological Conditions (IMC) were examined in one scenario to determine impact on performance and workload for the candidate procedures. The IMC condition used a cloud base of 250 feet Above Ground Level (AGL) to allow examination of possible aircraft behavior transitions while in IMC conditions

d) Traffic Conflict

Detection and avoidance of aircraft was used as a realistic secondary task from which to assess workload and spare capacity. Participants were provided with displays of traffic on the PFD, ND as well as in the visual environment. The visual environment for the study (Edwards Air Force Base airspace) was chosen in part as an environment with reduced visual clutter as compared to an urban environment to make it easier to visually identify aircraft traffic. The training day included instruction on the identification of aircraft and demonstration of other aircraft in the air or on the ground using the Out the Window as well as PFD and Navigations Display. The participants were instructed that there would be traffic in the data collection scenarios.

The test scenarios included four different traffic conditions. The first condition presented traffic that did not present a conflict and the remaining three traffic scenarios required the participant to maneuver to avoid a traffic conflict. The conflicts included slow preceding traffic, slow departing traffic, or traffic that was taxiing to the landing pad.

1) *Dependent Measures*

a) Flight Technical Performance

The Dependent Variables included flight technical performance, secondary task (traffic avoidance) performance, and participant ratings of aircraft controllability and workload.

Flight technical performance included measurement of airspeed, groundspeed, altitude, heading, track, vertical speed, and time to complete the landing. The performance criteria were selected based on a combination of performance criteria from ADS-33, [1] and a combination of airplane and helicopter FAA Airman Certification Standards (ACS) as guidance for determining Adequate (Commercial) and Desired (Airline Transport Pilot) performance [15][16][17][18][19]. In some instances, the performance criteria were relaxed or tightened to reflect the expected UAM approach and landing environment. Fig. 11 shows a sample of the approach performance criteria.

Performance Requirements	**Desired**	**Adequate**
Maintain Lateral and Vertical track within:	1/2 dot	1 dot
Maintain airspeed on approach within:	+/-5 kts	+/-10 kts
Touchdown with aircraft CG within X ft of landing circle:	5ft	10ft
Touchdown sink rate within:	240fpm	360fpm
Longitudinal groundspeed at touchdown:	+2/-0.5 kts	+4/-1 kt
Lateral groundspeed at touchdown:	1kt	2kts
Heading at touchdown within:	5 deg	10 deg

Fig. 11. Sample Approach performance criteria

The instructions for the approach task also included two additional performance criteria. Pilots were instructed to not overshoot the landing zone as defined by the forward edge of the adequate performance landing circle. to complete the task in as short a time as possible. The time criteria were defined with and expectation that battery powered eVTOL aircraft would have limited time in Thrust-Borne flight (e.g., hover) due to temperature and endurance (i.e., storage and consumption) limitations.

b) Pilot Ratings

Pilots provided feedback through two different rating scales, a post-study questionnaire and discussion throughout the study.

The Cooper-Harper Handling Qualities Rating scale [20] was used to assess psycho-motor workload and pilot compensation required for flying the LPC in the different AHA conditions across the approach segments. The use of the Cooper-Harper scale allowed assessment across previous studies as well as a measure to ensure that the aircraft handling qualities were acceptable for the test tasks.

The Bedford Workload Rating scale [21] was used to assess mental workload for the combined task of controlling the aircraft, monitoring flight performance and hover automation, and maintaining visual separation from other aircraft.

Participants were presented with a Questionnaire at the conclusion of the study. Participants were asked to provide general thoughts and feedback first, and presented with specific questions about difficulties with the conditions they might have experienced including the aircraft, environment, automation, pilot interfaces, and eye tracker after.

c) Eye Tracking

All participants were asked to wear eye tracking glasses. The glasses were fitted during the training day. The eye tracking glasses had replaceable lenses that could be adjusted to match the prescription for those participants using vision correction. The eye tracking was tuned for five Areas of Interest (AOI) Out The Window (OTW), PFD, ND, SD, and Chin windows (Fig. 1, Fig. 2), but allows for specification of additional AOIs in post-study analysis.

D. Data Collection Process

The VMS tasks consisted of 45 approaches divided into three sessions throughout the day. Participants in the first session. flew 6 full approaches followed by 8 approaches starting on a base leg that required a turn to the final approach course. The second session continued the base turn initial point for 16 approaches. The third session started the approach on the final approach course prior to the Final Approach Fix.

The Independent Variables were randomly assigned across the approaches with a few exceptions. The full approach was only conducted in the AHA-0 automation condition with only calm winds or Right Quartering Headwinds due to the limited number of full approaches conducted. The second session had randomly assigned Degraded visual conditions and winds. The third session was the session to receive a randomly assigned direct (17knot) crosswind and Instrument Meteorological Conditions.

IV. Discussion

The eVTOL aircraft industry has proposed many novel aircraft, automation, pilot interface and operational concepts. This paper reported on the development, conduct and high-level preliminary takeaways from the Automation Enabled Pilot study 2 (AEP-2). The AEP-2 study examined pilot performance using different assistive automation and display elements using maneuvers that contain representative elements of proposed approaches for Urban Air Mobility operational concepts, and industry representative aircraft, command concepts and pilot interfaces. AEP-2 selected representative concepts to examine the impact of pilot interface changes that are currently without regulatory guidance on performance of representative eVTOL approach tasks.

Due to delays in the start of the study, data collection was not completed until the end of June 2024 and subsequent analysis is not complete, but there are a few high-level discussion items.

A limitation introduced by the novelty of the many different aircraft, automation, interface, and operational concepts in industry is a lack of operationally representative participants for the AEP study series. As such participants in the AEP-2 were pilots with decision making roles for development and evaluation eVTOL aircraft airworthiness, Powered-Lift pilot qualifications and training requirements either in industry or as a regulator. This limitation required specialized participant training for the concepts developed for the study, but participant availability concerns limited the training to one day.

A benefit to the use of such qualified participants is insight into the current state of simulation development. The participants reported that the operational concepts, aircraft, command concepts and pilot interfaces were well aligned with current and future concepts and provided a good baseline for research evaluation. Participants also reported that the training provided for the study provides insight into future requirements for pilot training and aircraft evaluation. The training for the AEP-2 study is discussed in greater detail in [12].

The training schedule was designed with extra time to accommodate varying background and experience levels. All participants reported that the training they received was adequate for the study, however, some participants without significant prior VTOL aircraft experience found the data collection runs to be more challenging. One participant without helicopter flying experience did report that experience flying VTOL drones with augmented control systems with behavior like the AEP-2 flight control systems concepts was useful. Participants also reported that the 30-minute VMS familiarization sessions were adequate to adapt to differences between ACEL-RATE and the VMS.

The limited training time is inadequate to control for habits and muscle memory for different inceptor configurations (e.g., helicopter cyclic and collective). As a mitigation, participants were directed to advise researchers during data collection if they made an incorrect control movement due to interference from flying other aircraft types so that the trial could be run again. Some participants also reported that they did reference the AHA condition information on the Systems Display prior to starting a data collection run to remind themselves of the expected behavior. Over the course of the study, participants asked for a small number of re-runs (approximately 1%). Following the study the participants reported that it was not a significant impact on flight performance.

The participants did not report difficulty with flying the approaches in different ceiling or visibility conditions. It was assumed for AEP-2 development that the navigation precision required for UAM operations dictates the use of instrument procedures and the appropriate existing instrument approach procedures [4] required use of Flight Director or Autopilot. Participants reported that the approaches were easy to fly using the Flight Director but stated that industry has not yet considered IFR operations, so it is unclear if the assumptions made for AEP-2 are valid.

Other concerns included the simulator visual cueing environment. The Field of View and resolution of the VMS visual system were reduced compared to the ACEL-RATE simulator. Most participants reported that it was not difficult to acquire the landing site with the visual cueing, but a couple of participants did report some difficulty. It has not been determined if any difficulty in acquiring the landing site is a result of different pilot techniques. Future analysis will examine a correlation with the use of the map, chin, and belly camera usage. During the data collection runs, no participants were observed to use the chin camera, but most participants did use the belly camera for precision landing information. Participants reported that they would have preferred a wider Field of View and reference markings for the belly camera to address these concerns. Participants overall reported that they could see the conflicting traffic but that it was difficult to judge distance from other airborne aircraft.

Ten participants used the eye tracking glasses for all runs. Three participants remarked that the glasses did cause a minor interference but did not request to remove the glasses. Nine participants required vision correction and were provided with corrective lenses The participants reported that the interference was due to vision correction that didn't match their prescription due to a lack of bifocal or progressive type lens options. One participant remarked that the eye tracking glasses were fatiguing and removed the glasses.

Participants were asked if the concepts as presented would be acceptable for flight test or for operational use. Most participants felt that the interfaces and command concepts could be acceptable for flight test but did not feel that the concepts were ready for live flights with operational pilots as tested in the study. The time criteria have been identified as more restrictive than would be expected in nominal operations to drive urgency, reflect real-world time pressure, and expose potential deficiencies in the automation conditions. This aligns with the performance criteria used in the study which were designed to be operationally realistic but also to stress the concepts to identify differences in conditions and for the results of AEP-2 to contribute to the development of flight tests in the future.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the NASA Ames Vertical Motion Simulator (VMS) staff, especially Matthew Blanken, Samuel Orth, and Tejas Lotay.

REFERENCES

[1] Anon., "Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft," Tech. Rep. ADS-33E-PRF, United States Army Aviation and Missile Command Aviation Engineering Directorate, Mar. 2000. URL https://www.amrdec.army.mil/amrdec/rdmr-se/tdmd/Documents/ads33front.pdf.

[2] M. S. Feary, Kaneshige, J, T. Lombaerts, K. Shish, and L. Haworth, "Evaluation of Novel eVTOL Aircraft Automation Concepts," (AIAA Aviation 2023 Forum, San Diego, CA, 12-16 June 2023

[3] Anon., FAA, 2023, "Urban Air Mobility Concept of Operations v2.0," "Department of Transportation, Federal Aviation Administration, 26 Apr, 2023

[4] Anon., "FAA Advisory Circular 90-101A Approval Guidance for RNP Approaches with AR," Department of Transportation, Federal Aviation Administration, 9 Feb, 2016

[5] FederAA Advisory Circular 90-107, "Guidance for Localizer Performance with Vertical Guidance and Localizer Performance with Vertical Guidance Approach Operations in the U. S. National Airsace System," Department of Transportation, Federal Aviation Administration, 11 Feb 2011.

[6] Johnson, W., Silva, C., and Solis, E., Concept Vehicles for VTOL Air Taxi Operations, AHS Specialists' Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, 2018.

[7] J. Kaneshige, T. Lombaerts, K. Shish, and M. Feary, "Command and Control Concepts for a Lift Plus Cruise Electric Vertical Takeoff and Landing Vehicle," AIAA Aviation 2023 Forum, San Diego, CA, 12-16 June 2023

[8] J. Kaneshige, T. Lombaerts, K. Shish, and M. Feary, "Simplified Vehicle Control Concept for a Lift Plus Cruise eVTOL Vehicle," AIAA Aviation 2024 Forum, Las Vegas, NV, 29 July – 2 August 2024

[9] Anon., United States Standard for Terminal Instrument Procedures (TERPS), ORDER8260.3D, Department of Transportation, Federal Aviation Administration, February, 16, 2018.

[10] Anon., "FAA Advisory Circular 150/5390-2C, Heliport Design, "Department of Transportation, Federal Aviation Administration, 5 Jan, 2023

[11] D. Webber, "UAM Helicopter Surrogate Flight Test Report," AAM-NC-070-001, NASA, 2022. URL https://www.faa.gov/training_testing/testing/test_standards/.

[12] L. Haworth, M. Feary, A. Villa, B. Baron, M. Steglinski, J. Kaneshige, K. Shish, N. Iwai, K. Monk, T. Lombaerts and J. Archdeacon, "Training the Powered Lift Evaluation Pilot," AIAA/IEEE 43rd Digital Avionics Systems Conference, San Diego, CA, 29 Sep – 3 Oct, 2024

[13] Anon., "Draft FAA Advisory Circular 21.17-4 Type Certification – Powered Lift"

[14] Anon., "FAA 14 CFR 91.155 Basic VFR Weather Minimums"

[15] Anon., "FAA Commercial Pilot for Airplane Category (FAA-S-ACS-7B)" Department of Transportation, Federal Aviation Administration, 31 May 2024

[16] Anon., "FAA Airline Transport Pilot and Type Rating Practical Test Standards for Rotorcraft Category Helicopter Rating (FAA-S-8081-20A)" Department of Transportation, Federal Aviation Administration, 31 May 2024

[17] Anon., "FAA Airline Transport Pilot and Type Rating for Airplane Category (FAA-S-ACS-11A)" Department of Transportation, Federal Aviation Administration, 31 May 2024

[18] Anon., "FAA Commercial Pilot for Rotorcraft Category Helicopter Rating (FAA-S-ACS-16)" Department of Transportation, Federal Aviation Administration, 31 May 2024

[19] Anon., "FAA Airline Transport Pilot and Type Rating for Powered Lift Category (FAA-S-ACS-17)" Department of Transportation, Federal Aviation Administration, 31 May 2024

[20] G. E. Cooper, and R. P. Harper, "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, 1969.

[21] A. H. Roscoe, and 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