Evaluation of Novel eVTOL Aircraft Automation Concepts

Michael S. Feary[1], John Kaneshige, [2] Thomas Lombaerts[3], Kimberlee Shish[4], and Loran Haworth[5]
NASA Ames Research Center, Moffett Field, CA, 94035, USA

As new electric propulsion technologies have matured, many new electric propulsion Vertical Takeoff and Landing (eVTOL) aircraft concepts have been proposed. These new aircraft concepts enable the creation of new aviation markets including Urban Air Mobility (UAM) but also pose new challenges in safety assurance. One early challenge is the evaluation of the diverse aircraft configurations and accompanying advanced control systems and automation designed to aid controllability. This paper describes a research activity to propose candidate means of evaluation for the aircraft concepts and automation in the context of UAM operations. The research activity proposes the adaptation of an evaluation design standard used by the military for advanced rotorcraft along with proposed descriptions and definitions to support evaluation of diverse automated concepts in the civilian eVTOL community.

I. Nomenclature

H_{FAF} = Height at Final Approach Fix Above Ground Level (AGL)
V_{AT} = Approach Speed at threshold
V_h = Speed in Level Flight with Max Continuous Power
V_{MO} = Max Operating Speed
V_{NE} = Never Exceed Speed
V_S = Stall or minimum steady flight speed at which the aircraft is controllable
V_{TOSS} = Takeoff Safety Speed for Category A rotorcraft
V_X = maximum angle of climb speed
V_Y = best rate of climb speed

II. Introduction

The aviation industry has seen a surge in the development of novel aircraft configurations, operations and increasingly automated systems. A gap has been exposed between the pace of development and adequate evaluation methods to ensure the safety of the capabilities in operation. Aircraft regulators are facing an unprecedented diversity of applicant aircraft configurations in aviation segments generally referred to as Advanced Air Mobility (AAM). AAM has been defined as "a safe and efficient system for air passenger and cargo transportation, inclusive of small package delivery and other urban drone services, which supports a mix of onboard/ground-piloted and increasingly autonomous operations." [1, 2]

This paper describes a research activity aimed at developing evaluation methods that accommodate a range of

---

[1] Aerospace Technologist, Human Systems Integration Division, Mail Stop 262-4, AIAA member, email: michael.s.feary@nasa.gov

[2] Computer Engineer, Intelligent Systems Division, Mail Stop 269-1, AIAA member, email: john.t.kaneshige@nasa.gov

[3] Aerospace Research Engineer, KBR, Intelligent Systems Division, Mail Stop 269-1, AIAA Associate Fellow, email: thomas.lombaerts@nasa.gov

[4] Aerospace Engineer, Intelligent Systems Division, AIAA Member, email:kimberlee.h.shish@nasa.gov

[5] Consultant, SJSUF, Human Systems Integration Division, email: loran.a.haworth@nasa.gov

automated aircraft systems (i.e., pilot on-onboard, remotely operated, or autonomous) and a diversity of aircraft configurations, specifically aircraft with electric propulsion and Vertical Takeoff and Landing (eVTOL) capabilities. The research activity described in this paper focused on the aircraft automation and operational concepts enabled by electric propulsion technologies rather than the details of electric propulsion for aircraft.

The initial research efforts propose to adapt an evaluation methodology used by the military for assessing VTOL capable aircraft flying and handling qualities against mission requirements referred to as U.S. Army Aeronautical Design Standard 33 (ADS-33). The ADS-33 standard was developed with support from NASA [3, 4], other branches of the U.S. military and the FAA to assess rotorcraft and other VTOL aircraft with novel handling characteristics against military requirements. The current version at the time of writing is ADS-33E [5].

This paper describes the development of industry representative aircraft system concepts and evaluation infrastructure (e.g., eVTOL aircraft models, automation, procedures and urban scenery databases for visual systems, scenarios, etc.) used to support the development of evaluation methods for eVTOL aircraft and automation concepts and results from a simulator study to examine the efficacy of flight test maneuvers. While industry AAM aircraft concepts are diverse, the current focus includes onboard pilots reflecting the state of the industry until the concept of operations mature to the point to allow remote piloting or autonomous operations.

Referred to as the NASA Automation Enabled Pilot study -1 (AEP-1), the study described is a part of a series of studies funded by NASA and the FAA to establish Flight Test capabilities (e.g., Maneuvers, test courses, instructional materials), for a variety of uses, including support for the development of a Means of Compliance for certification of novel AAM aircraft and automated concepts. The maneuvers are intended to be operationally representative. focused on the assessment of various automation configurations using one industry representative aircraft concept and expected flight test maneuvers. AEP - 1 provided and opportunity for development and validation of simulation resources including updates to the aircraft performance models, pilot interface, test course infrastructure and flight test performance displays.

The AEP-1 study was part of a series that also included two activities sponsored by the FAA, referred to as V/STOL Evaluation – 1 (FAAVE – 1), conducted in June 2021 and FAAVE -2 conducted in June 2022. The activities focused on developing materials to support assessment of piloted eVTOL aircraft with Indirect Flight Control Systems (IFCS), reflecting the state of the leading industry airworthiness applications and FAA needs. A particular focus is the use of IFCS require design decisions about desired behavior as the aircraft transitions between forward flight and hover and vice-versa. IFCS also enable aircraft applicants to deviate from conventional pilot station configurations (e.g., cyclic, and collective inceptors, pedals). Some of these transitions occur regardless of aircraft configuration (e.g., airmass to ground-referenced flight, envelope protection) while others (e.g. the transition from wing-borne to thrust-borne flight) will vary with aircraft configurations (e.g. Tilt-rotor, Tilt-Wing, Lift Plus Cruise, etc.).

This paper describes the development and assessment of flight test maneuvers for evaluation of automation concepts. A companion paper [6] describes the details of the control systems developed and results of handling quality assessment for the aircraft configuration and different control system concepts.

III. Evaluation of Novel AAM Aircraft Configurations

The quantity and diversity of AAM eVTOL aircraft configurations (e.g., Multi-Copter, Tilt-Rotor, Tilt-Wing, Lift-Plus-Cruise, etc.) [7] has not been seen since the early days of aviation and have enabled the possibility of new operational concepts such as Urban Air Mobility. Despite the diversity in configurations many of these concepts share a challenge of handling complexity and challenges without augmentation. A common approach to mitigate these challenges for many of these concepts is the use of Indirect Flight Control Systems (IFCS), commonly referred to as “Fly-by-Wire” or FBW. IFCS replace mechanical linkages between the pilot and flight control surfaces with electrical signals that are interpretations of the pilot actions by an onboard computer. These signals are sent to actuators at the control surfaces. In addition to IFCS providing reduced weight and reliability advantages, the adoption of IFCS has been used to enhance stability, maneuverability and controllability of aircraft and has enabled the development of safety functions (e.g., envelope protection).

While the development of the AAM aircraft configurations and automation concepts has been rapid and diverse, the evaluation methods needed to ensure safety of these novel concepts has not kept pace and a gap has become apparent. The introduction of maneuver demand Indirect Flight Control Systems prompted the FAA to develop new methods of compliance. The Handling Qualities Rating Method [8] provided an approach to a pilot rating of the acceptability of combinations of failure cases, atmospheric disturbances, and flight envelope probabilities. This approach has been successfully used for many years in the evaluation of IFCS on transport category airplanes as part of the special conditions.

To date, aircraft with IFCS have been certified under “Special Conditions” [9], which refers to the need to evaluate a novel feature for a particular aircraft design, however the “Special Condition” approach is thought to be unlikely to scale to the extent needed to evaluate the large number of potential AAM aircraft applicants. The requirement for a special condition is to establish “a level of safety equivalent to that established in the regulations” [9] which can require significant resources for both the applicant and the regulator. Applicants are likely to be further hindered by a lack of operational data, which is typically used to establish an equivalent level of safety. In addition, if the environment and infrastructure requirements are not already well defined, establishing aircraft performance requirements will be difficult.

An examination of methods to help sort through the diversity and complexity of AAM aircraft and automation configurations led to a method developed by the military and NASA referred to as Aeronautical Design Standard-33 (ADS-33) [5]. ADS-33 was developed in the 1970’s to support the evaluation of the U.S. Army’s Light Helicopter Experimental (LHX) program. The LHX program and Comanche helicopter had several innovations, including a digital Fly-By-Wire flight control system and proposals for novel inceptor configurations. The standard describes methods for the flight test and analysis of aircraft handling characteristics, however for the purposes of this paper the method provides a basis for developing flight test maneuvers based on mission requirements, referred to as Mission – Task -Elements.

The objective of the Mission -Task-Element approach described in ADS-33 is to expose potential handling deficiencies in aircraft performing various aspects of their intended “missions”. By defining performance criteria that are associated with expected flight operations, the evaluation maneuvers can be agnostic of aircraft or automation configuration and are therefore well suited for assessment of the diversity of novel AAM aircraft and automation concepts. This is demonstrated in ADS-33 by applying subsets of the catalog of described maneuvers to named missions (e.g., “Attack”, “Scout”, “Utility”, “Cargo”) as illustrated in Fig. 1. In addition to decades of successful use for evaluation of piloted aircraft, ADS-33 methods have been shown to accommodate evaluation of a wide range of potential pilot (onboard or offboard) interfaces enabled using IFCS and evaluation of different VTOL aircraft configurations, including Unmanned Aerial System (UAS) [10]. The performance criteria associated with the Flight Test Maneuvers also align with the FAA transition to Performance Based Aviation Regulations [11].

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

Notes: ✓ = Suggested maneuvers to apply with appropriate performance standards.
L = Limited agility
M = Moderate agility
A = Aggressive agility
T = Target Acquisition and Tracking

Fig. 1 ADS – 33E-PRF Mission Task Element maneuvers

The set of maneuvers described in ADS-33E provide a basis for the Flight Test Maneuvers. A subset of the maneuver list is shown in Fig. 1 were selected for the initial catalog, based on the ability to expose handling deficiencies in the proposed aircraft and operational concepts. The expectation is for the initial catalog to be extended and for individual maneuvers to be selected and tailored to suit the operational concept for the Type Certification applicant.

The wide diversity of novel proposed aircraft and automation configurations will lead to development and refinement of the maneuver specifications to uncover potential deficiencies, but it is hoped that the candidate maneuvers will be a starting point for future development. The Flight Test maneuvers developed from the research effort are intended to be a starting point for a new Means of Compliance for the evaluation of handling qualities for the new Powered Lift class of aircraft.

IV. The Pilot-Automation-Interaction framework

Over the course of the study, it became apparent that existing characterizations of Human-Automation Interaction [12,13], were not sufficient to describe the different aircraft automation configurations to the extent needed. An adaptation of Rasmussen's abstraction hierarchy [14, 15] which integrates descriptions of the mission performance requirements with descriptions of the automation functional capabilities [16] was used as the basis for a detailed characterization of aircraft automation dimensions referred to as the Pilot-Automation framework (PAI). Research priorities for NASA and FAA focused only developing evaluation methods for the Command Concepts (CC) and associated and display elements of the framework. Fig. 2 shows an overview of the Command Concept (CC) dimension of the framework.

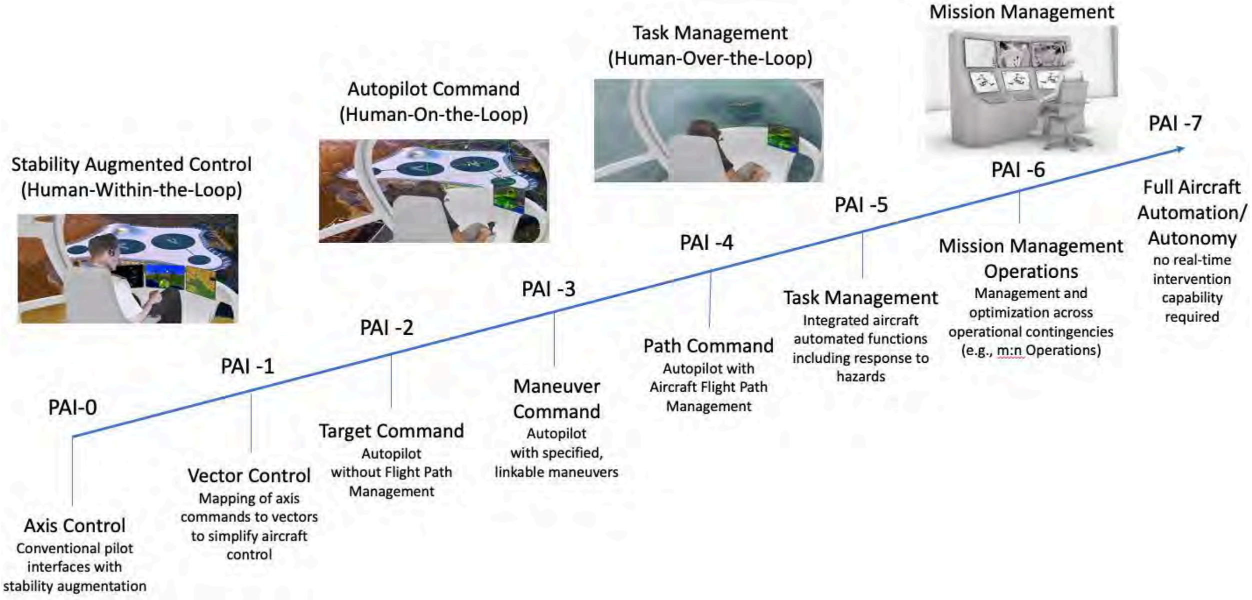


Fig. 2 Pilot-Automation-Interaction Framework – Command Concept Description

The PAI framework is a characterization of real-time functional state rather than a description of minimum or maximum capability. For example, if an autopilot is engaged while in CC-0, the aircraft moves to the CC-2 configuration. Similarly, an aircraft that is being supervised in CC-6 is selected for control by a single pilot the Control Concept would correspondingly change to reflect the new configuration. The framework is expected to evolve as automation functions and use of different combinations of functions mature.

A. Command Concepts

The Command Concept framework currently consists of eight reference capabilities:

0. "Axis Control" refers to conventional control strategies where inceptor movement is linked to pitch, roll, yaw, heave and longitudinal thrust (or combined heave/longitudinal for tiltrotor/tiltwing) vectors for commands. For VTOL-capable aircraft pilot inceptor actions may result in different aircraft behavior as the aircraft transitions between different flight regimes (e.g., hover to forward flight, forward flight to hover)
1. "Vector Control" refers to a mapping of the pitch, heave and thrust axis commands to vertical and longitudinal vector-based commands, creating flexibility as to inceptor configurations. The pilot inputs a speed magnitude and direction, and the aircraft automation manages the control axes to maintain consistent

behavior across speed regimes and reference frames. For example, depending on speed, a longitudinal inceptor input may result in either a heave or pitch command and a thrust inceptor input may result in groundspeed or airspeed command.

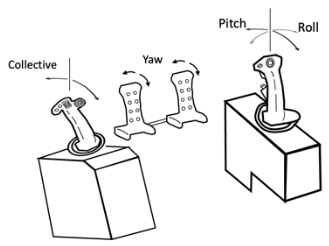
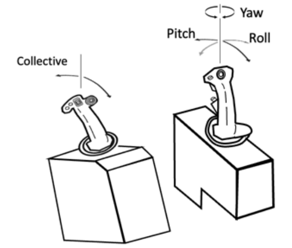
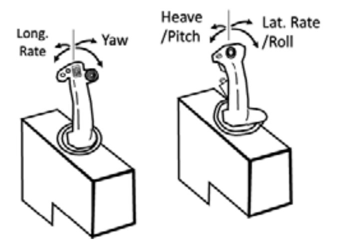
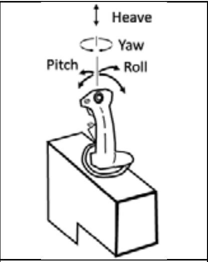
2. “Target Command” refers to aircraft automation managing aircraft behavior to achieve a target (e.g., altitude speed, direction) the pilot has commanded either through an inceptor or other input device (e.g. autopilot control panel). In target command, only one target is specified per vector, these targets are also referred to as “tactical” targets.
3. “Maneuver Command” refers to an ability for the pilot to command how the automation achieves a target. Maneuvers are a sequence of target commands that can be linked to result in a motion-based trajectory. Conventional Flight Management Systems have this capability. Examples of maneuvers include flying to and over or by a waypoint, Holds, and Approaches.
4. “Path Command” refers to a capability to optimize the flight path and specify preferences for how the aircraft manages the flight path targets. Partial capability exists in Flight Management systems with aircraft performance models today, but also includes systems that dynamically replan to avoid hazards or assist with air traffic management.
5. “Task Management” refers to the ability of the aircraft automated systems to respond to specific tasks, regimes or phases of flight with minimal human interaction. Examples include automatic detection and avoidance of hazards while completing a mission segment with minimal human involvement.
6. “Mission Management” refers to the ability for the aircraft to manage all component systems and complete missions with minimal human involvement, including no human involvement for missions completed without unplanned events. This capability allows human supervision of multiple aircraft.
7. “Full Aircraft Automation/Autonomy” refers to automation that does not require human intervention to successfully complete a mission including modifying aircraft behavior to manage unplanned events.

B. Pilot Input Concepts

The Pilot Input framework consists of multiple combinations aligned to the task performance and automation requirements. Beyond PAI-0 the number of combinations of pilot input configurations increases to the point where notation is needed to describe the configuration. These include:

- Pointing Devices
- Text or character input
- Graphical User Interface
- Recognition; Gesture, Gaze, other
- Inceptors: The inceptor combinations are described by the number of axes controlled by each inceptor [17]., with sidesticks pictured. Examples of different inceptor configurations (including sidestick versions of a conventional cyclic and collective configuration) are shown in Table 1.

Table 1. Example Inceptor Configurations

			
2 + 1 + 1 Collective	3 + 1 Collective	2 + 2 Rate	4 + 0
2 axis inceptor for pitch and roll, separate inceptor for collective (heave)and pedals for yaw	3 axis inceptor for pitch, roll and yaw, separate inceptor for collective (heave)	2 axis inceptor for heave/pitch and a 2 axis inceptor for roll/translation and yaw	one inceptor for 4 axes (pitch, roll, yaw, heave)

C. Display Concepts

In this context “Displays” refers to multiple modalities (e.g., visual, auditory, haptic, etc.) and includes alerting. Together with input concepts, the display requirements will vary based on task performance and automation requirements. These requirements define the display elements and characteristics needed for information acquisition, analysis, decision making or execution of action requirements [18]. For fully automated/autonomous functions the display requirements may be partially or fully eliminated, but mixed initiative systems are likely to require additional display support to make automated functions predictable and allow humans to respond in a timely manner. For example predictive and quickened displays may be needed to account for delays introduced by changing the pilot task from manual control to supervision.

Examples of command concepts, and interface (i.e. input and display) concepts will be described in more detail in the context of the AEP-1 study.

V. Automation Enabled Pilot Study -1 Development

The Automation Enabled Pilot study (AEP-1) was conducted as part of the NASA AAM Automated Flight and Contingency Management (AFCM) sub-project. The AEP activity was responsible for the development of the simulation and aircraft automation configurations, for the integration of the aircraft models and automation for the FAA studies, and an assessment of the Flight Test Maneuvers' ability to evaluate automation. The first FAA sponsored study (FAAVE-1) focused on an investigation and comparison of a baseline Quadrotor aircraft model [7, 22] against the newly developed Lift-Plus-Cruise model with a single flight control configuration. The concept used in FAAVE-1, referred to as Command concept -1 (CC-1) has similarities to the "Unified" flight command configuration [19, 20, 21]. The focus of the AEP-1 study was an evaluation of the ability of three selected Flight Test Maneuvers to assess different industry representative command and pilot interface concepts using an industry representative eVTOL (i.e. Lift-Plus-Cruise) aircraft model.

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

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

A. Aircraft model

A Lift–Plus–Cruise (LPC) aircraft concept was developed by NASA researchers [7, 22] as representative of a subset of AAM industry concepts used in the 6000-pound weight class. The LPC aircraft model for AEP-1 was configured with fixed-pitch blades for thrust in the vertical axis, with differential RPM across the motors mounted on the wing providing control [23]. Based on results of the FAAVE-1 activity, the thrust motor torque for the LPC model was increased to improve handling performance for hover and low speed maneuvering. AEP-1 also examined test course improvements based on findings in FAAVE-1. The LPC aircraft model did not include models of ground effect, atmospheric effects, or critical azimuth. Detailed description of the AEP-1 aircraft and handling performance results can be found in [6]. A depiction of the Lift Plus Cruise is shown in Fig. 3.

Fig. 3 NASA Lift Plus Cruise aircraft concept illustration

The Lift Plus Cruise (LPC) aircraft conceptual model was designed by NASA's Revolutionary Vertical Lift Technology's project, with high fidelity dynamics models generated by Advanced Rotorcraft Technology (ART) using FlightLAB. There are known limits for this vehicle's design, configuration, and control authority. The vehicle design has eight lifting propulsors and one pusher propeller. The lifting propulsors are of a fixed blade pitch angle and can be independently controlled by adjusting torque commands to achieve the desired Rotations Per Minute (RPM). At low speeds, differential control of the lifting propulsors is used for maneuvering and collective control for heave. The pusher propeller is controlled through variable blade pitch, operating at constant RPM. The vehicle also has flight control surfaces consisting of two ailerons, an elevator, and a rudder. While in cruise, at airspeeds above approximately 60 knots, the pusher propeller and flight control surfaces can provide sufficient control authority and response times fast enough to achieve acceptable handling qualities. However, when maneuvering using the RPM controlled lifting propulsors, the vehicle has a slow response. In addition, the pusher propeller is located four feet above the center of gravity of the aircraft. As a result, as thrust is increased on the pusher propeller, it introduces a pitch down moment (or pitch up moment as thrust is pulled back). At cruise speeds, the elevator can more quickly compensate for this; however, at lower speeds, the lifting propulsors will be slow to arrest. Therefore, for this vehicle, deficiencies are expected through transition and hover, especially for higher aggression maneuvers.

Aerodynamic changes pose a challenge for lift plus cruise designs. As the vehicle decelerates and transitions off the wing, the loss of lift may produce unintended descent. Likewise, as the vehicle picks up speed, the increased lift may result in unintended pitch up and climbing. With the wing and vertical tail, this vehicle is susceptible to weathervane in a crosswind. In transitioning from forward flight to hover (and vice versa), strategies to manage crab and sideslip can vary but result in challenges with rudder saturation as effectiveness is lost at slower speeds and lifting propulsors may be slow to compensate.

The LPC aircraft also exhibits deficiencies when transitioning on and off the wing, due to pitching moments associated with loss of lift, reduced directional control while transitioning from aerodynamic control surfaces to differential RPM control and reduced longitudinal control as the pusher propellor is disengaged.

B. Flight Control and Command Concepts Architecture

Investigations into proposed industry eVTOL concepts led to the identification of several Indirect Flight Control Systems (IFCS) industry representative automation and pilot interface configurations. The combinations of different control allocations, pilot inceptor, display and automation functions (e.g., autopilot, envelope protection) were too complex to describe independently, therefore an underlying control architecture was developed to support the different aircraft configurations (6, 24).

The architecture provides stability and control augmentation for rotational (pitch, roll, yaw) and translational (heave and thrust) axes, envelope protection, and mappings from outer loop command system to the inner loop controls. An overview of this architecture is shown in Fig. 4.

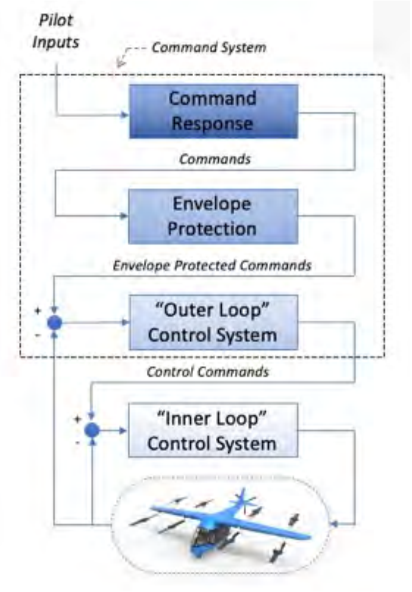


Fig. 4 Command Systems Architecture

The inner loop control system handles control allocation and mixing strategies for the control effectors. It consists of mode specific controllers which transition automatically as a function of airspeed. The rotational control modes include Attitude Command Attitude Hold (ACAH) and Rate Command Attitude Hold (RCAH) for pitch and roll control, and Rate Command Direction Hold (RCDH) and Turn Coordination (TC) for yaw control. Translational control modes, used at slower speeds include Rate Command Height Hold (RCHH) and Angle-of-Attack Command (AOAC) for heave and Acceleration Command Speed Hold (ACSH) for thrust.

The outer loop control system maps command responses (e.g., from pilot inputs) to the inner loop control modes. The outer loop control system is responsible for converting across reference frames (e.g., body axis, earth-referenced) and from angles to angular rates.

A distinguishing characteristic of VTOL aircraft is the ability to transition between a low-speed or hovering flight regime to a high-speed flight regime. The terms Hover regime, Transitional regime and Forward Flight regime refer to control mode and response type changes that are largely related to speed. The outer loop control system can provide additional stability and controllability during the transition from hover to forward flight as these transitions are particularly susceptible to handling difficulties.

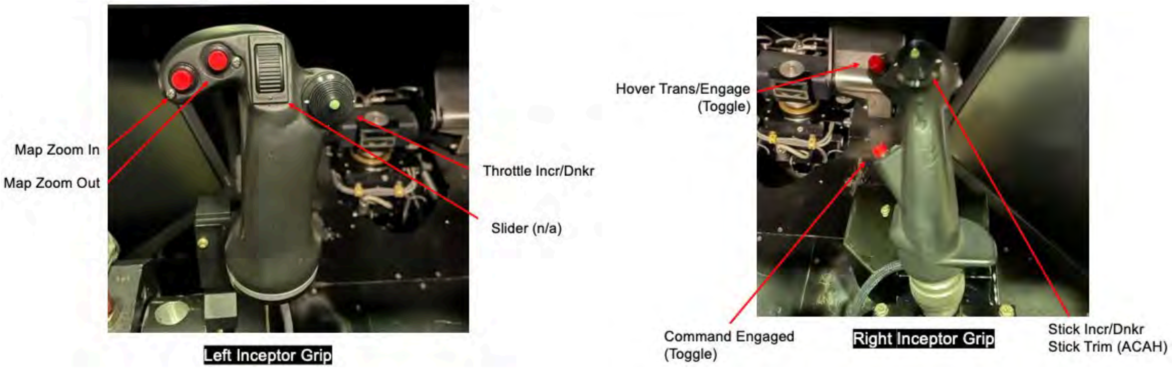
The Command Response, Outer Loop control and envelope protection functions comprise the Command System. The ability of the ADS-33 adapted Flight Test Maneuvers to evaluate different industry representative command systems is the focus the AEP-1 study. The combinations of industry representative command systems have been grouped and referred to as Command Concepts (CC). Pilots provide inputs to the Command Systems through inceptors or other input devices. The possible combinations of inceptor configurations can create a problem for evaluation of handling the aircraft, both from basic characteristics of the input configuration and interaction with individual pilot background.

C. AEP-1 Pilot Inceptors

While not a focus of the NASA or FAA sponsored studies, the inceptor characteristics (e.g., control force, gradients, bandwidth, breakout force) were designed to comply as much as previous research (25, 17) and ADS-33 section 3.6 as possible.

Section IV highlighted the multiple combinations of inceptor configurations made possible using Indirect Flight Control Systems. For the AEP-1 study, the possible configurations were reduced by resources available for the study and expectations about the most likely early industry configurations. Based on these considerations, the study focused on the use of sidestick inceptors without plunge or twist functionality and introduced sidestick yaw and direction control instead of pedals. These considerations resulted in examination of variations of 2 + 2 inceptor configurations. The specific configurations are described in the Command Concepts section.

The Vertical Motion Simulator (VMS) simulation inceptor hardware consisted of left and right 2-axis side-arm inceptors and rudder pedals. For development in the ACEL-RATE simulator, two passive, commercially available spring centered side-arm controllers were used. The VMS utilized high fidelity McFadden control loaders with custom inceptor grips. The flight control grips, and switch/button are illustrated in Fig. 5.



Left Inceptor Grip

Right Inceptor Grip

Fig. 5 AEP-1 VMS Inceptor grips

D. Hover Mode

All three Command Concepts feature a “Hover mode” function. The Hover mode is designed to improve the slow handling response and assist in providing the precision necessary for hover and landing. In previous studies, hover mode automatically engaged and disengaged; however, for AEP-1 Hover mode was selected manually for engagement through a button press on the right inceptor. If selected, hover mode engages when the aircraft decelerates below 10 knots groundspeed and disengages automatically when accelerating beyond 15 knots.

When the hover mode is armed, the vehicle will transition to hover by commanding a nominal 2.5 knot/sec deceleration rate, which can be overridden by applying inputs to the "thrust" stick. When the hover mode is engaged, thrust and lateral stick inputs will produce longitudinal and lateral vector commands.

While in hover mode, the aircraft uses a Translational Rate Command (TRC) ground relative controller, allowing inputs to command lateral and longitudinal velocities for all command concepts. TRC is used to achieve improved handling qualities and workload in hover and low speed prediction tasks. While this improves performance in these tasks, it introduces a mode transition, which could introduce mode confusion and we can expect to see issues with switching in aggressive maneuvers.

E. AEP-1 Command Concepts

Three Command Concepts were chosen to reflect the needs for evaluation methods. Type Certificate applications to the FAA which were identified as having onboard pilots with flight control augmentation, but not full automation. Fig. 6 shows the level of augmentation defined within the PAI framework. Deficiencies may vary across the PAI framework dimensions, but will include mode confusion, cross-coupling, display expectations, automation lags, remote operations, etc.

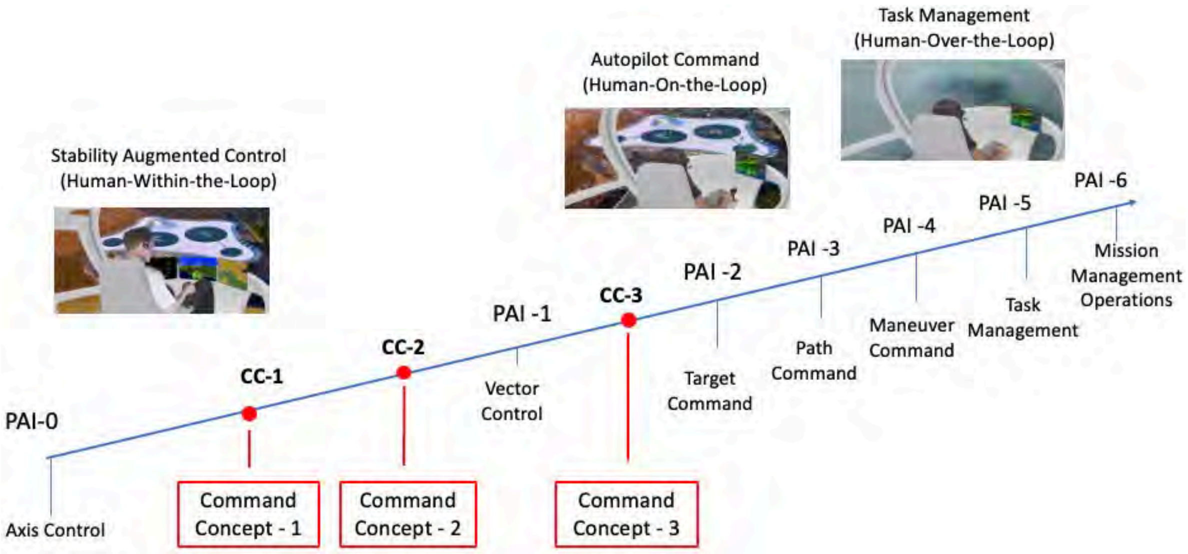


Fig. 6 AEP-1 Command Concepts in PAI framework

1. Command Concept-1 (CC-1)

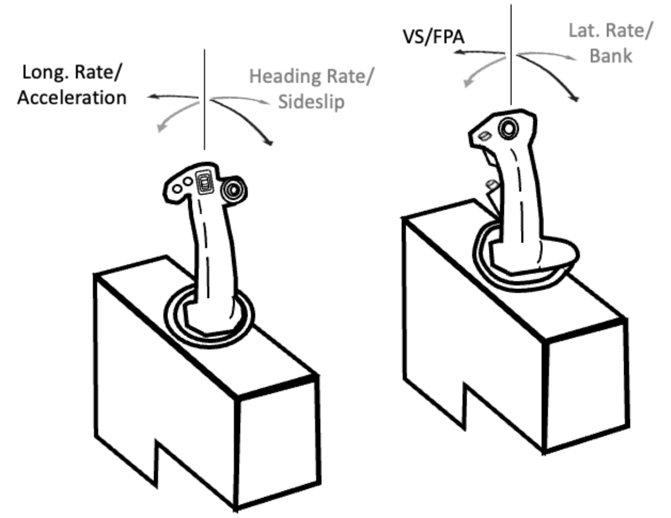
Command Concept -1 maps the pitch, heave and thrust axis commands to longitudinal and vertical vector-based commands reducing the number of inceptor axes from 5 to 4. Depending airspeed, Longitudinal stick inputs result in either Vertical Speed or Flight Path Angle (FPA) commands depending on the speed. Thrust inceptor movement will produce a velocity command, either groundspeed or airspeed. In AEP-1 an automatic trim system commands pitch in Thrust-Borne and Semi-Thrust Borne flight and Angle of Attack (AOA) in Semi-Wing Borne and Wing Borne flight regimes. In hover mode, thrust and lateral inceptor movements will command longitudinal and lateral vector commands, while longitudinal inceptor movement will command a vertical speed. The commands are mapped to the flight regimes as shown in Table 2.

Table 2. Command Concept-1 Command Response Types

CC-1	Inceptor	(Auto. Trim)	Thrust Inceptor	Pedal/Stick	Longitudinal Inceptor	Lateral Inceptor
Hover	Move	(Pitch Trim)	Longitudinal Rate	Heading Rate --- Heading Hold	Vertical Speed	Lateral Rate
	Release		Longitudinal Position		Altitude	Lateral Position
Thrust-Borne	Move		Acceleration Command --- Speed Hold		Vertical Speed Rate Command --- Vertical Speed Hold	Bank Command --- Bank Hold
	Release					
Semi-Thrust Borne	Move					
	Release					
Semi-Wing Borne	Move	(AoA Trim)		Sideslip Command --- Sideslip Hold	FPA Rate Command --- FPA Hold	
	Release					
Wing-Borne	Move	- - -				Bank Rate
	Release					Bank

CC-1 requires two-handed operation. Command Concept-1 also opens the possibility of multiple inceptor configurations. Fig. 7 shows the mapping for inceptor commands in Command Concept -1.

Inceptor Configuration- 1 (IC-1)



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

Fig. 7 Inceptor Configuration - 1

Handling deficiencies predicted for CC -1 are expected to result from the two-handed operation and a change in the mapping of inceptor to the eventual axes of control (pitch, heave, thrust, yaw) during the transition to hover.

2. Command Concept-2 (CC-2)

Command Concept -2 simplifies CC-1 by converting roll and yaw axis commands to heading and lateral velocity commands. This enables one handed operation when lateral and longitudinal thrust commands are placed on the same inceptor. The conversion to lateral velocity commands requires a filter to be added while in Wing-Borne or Semi-

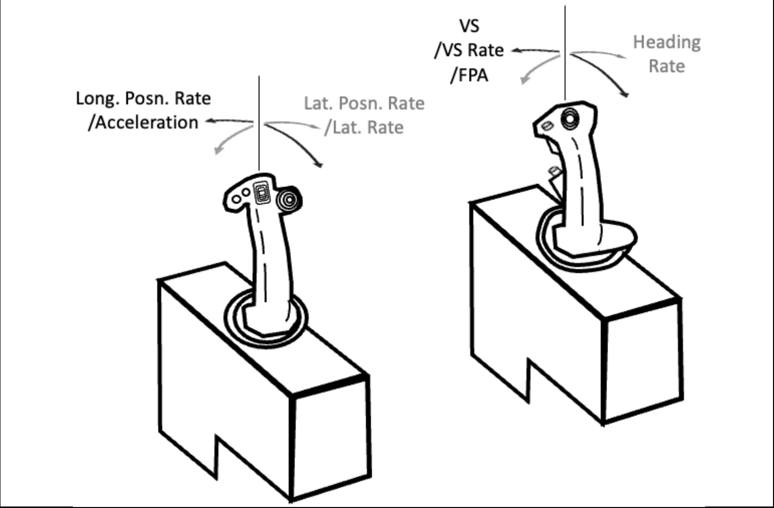
Wing Borne flight, to resolve negative sideslip commands that occur due to the interaction between turn coordination and lateral velocity commands and therefore introduces a new possible source of a handling deficiency.

Table 3. Command Concept -2 Response Types

CC-2	Inceptor	(Auto. Trim)	Thrust Inceptor	Pedal/Stick	Longitudinal Inceptor	Lateral Inceptor
Hover	Move	(Pitch Trim)	Longitudinal Position Rate	Lateral Position Rate	Vertical Speed	Heading Rate Command --- Heading Hold
	Release		Longitudinal Position	Lateral Position	Altitude	
Thrust-Borne	Move		Acceleration Command --- Speed Hold	Lateral Rate Command --- Lateral Rate Hold	Vertical Speed Rate Command --- Vertical Speed Hold	
	Release					
Semi-Thrust-Borne	Move					
	Release					
Semi-Wing-Borne	Move	(AoA Trim)			FPA Rate Command --- FPA Hold	
	Release					
Wing-Borne	Move	- - -				
	Release					

CC-2 allows for one-handed operation in hover. Fig. 8 shows the mapping between the inceptor movements and the commands for Command Concept -2.

Inceptor Configuration- 2 (IC-2)



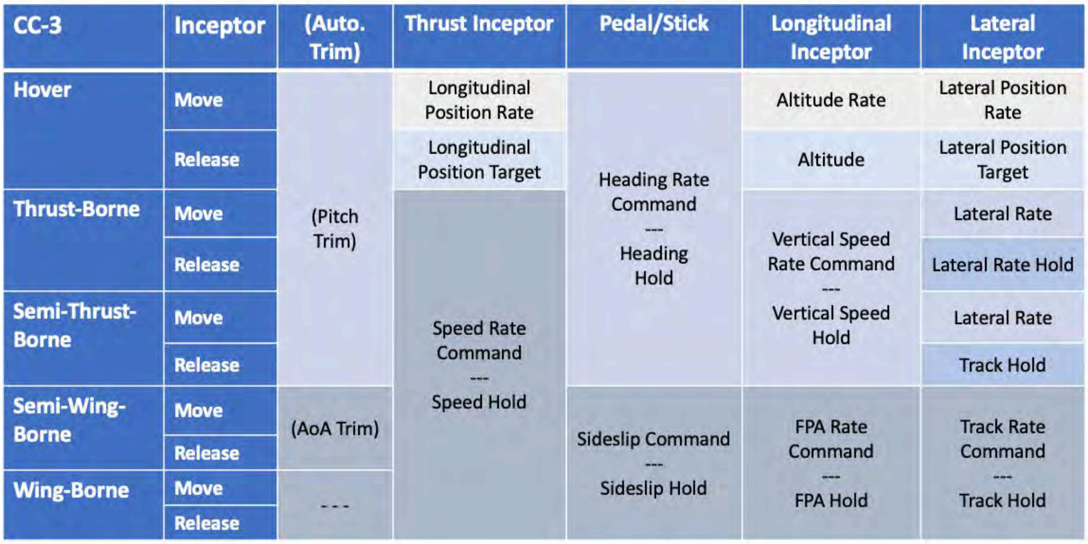
2+2 Rate
Right Inceptor = Vertical Speed/FPA Rate and Heading Rate
Left Inceptor = Longitudinal Position/Rate or Acceleration and Lateral Rate/Position Rate

Fig. 8 Inceptor Configuration - 2

Predicted deficiencies for Command Concept -2 stem from a change in behavior during the deceleration and acceleration phases.

3. *Command Concept-3 (CC-3)*

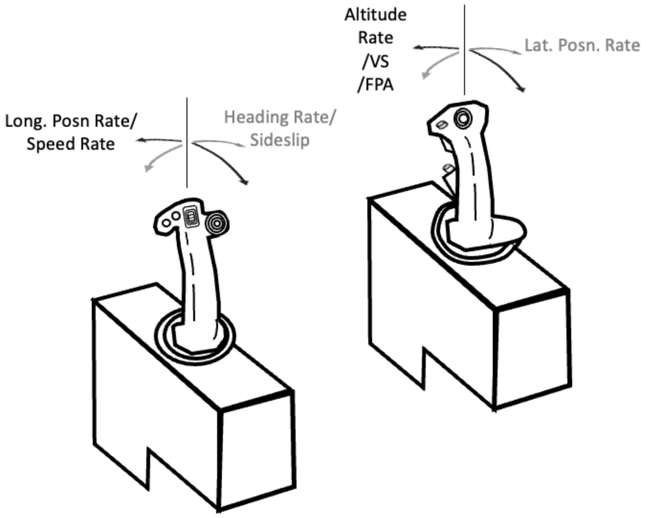
Command Concept – 3 is the most automated of the concepts under investigation. In CC-3 roll commands are mapped to a lateral vector-based command, and lateral stick inputs produce lateral velocity or track angle commands. When the hover mode is engaged, thrust and lateral stick inputs will produce longitudinal and lateral target commands that will move the location of a command hover point with respect to the heading of the vehicle. The addition of a control loop to allow the commanded hover point slows the responsiveness and to an extent that required the use of a predictive display to mitigate PIO. The use of a predictive display alters the nature of a task if the task is expected to be conducted by predominantly using visual cues in the external environment.



CC-3	Inceptor	(Auto. Trim)	Thrust Inceptor	Pedal/Stick	Longitudinal Inceptor	Lateral Inceptor
Hover	Move	(Pitch Trim)	Longitudinal Position Rate	Heading Rate Command --- Heading Hold	Altitude Rate	Lateral Position Rate
	Release		Longitudinal Position Target		Altitude	Lateral Position Target
Thrust-Borne	Move		Speed Rate Command --- Speed Hold		Vertical Speed Rate Command --- Vertical Speed Hold	Lateral Rate
	Release					Lateral Rate Hold
Semi-Thrust-Borne	Move					Lateral Rate
	Release					Track Hold
Semi-Wing-Borne	Move	(AoA Trim)		Sideslip Command --- Sideslip Hold	FPA Rate Command --- FPA Hold	Track Rate Command --- Track Hold
	Release					
Wing-Borne	Move	- - -				
	Release					

CC-3 allows for one-handed operation in hover. Fig. 9 shows the mapping between the inceptor movements and the commands for Command Concept -3. CC-3 allowed for simplified track control, but introduced additional lag in the flight controls, requiring the addition of a predictive display.

Inceptor Configuration- 3 (IC-3)



2+2 Rate

Right Inceptor = Altitude Rate/Vertical Speed/FPA Rate and Lateral Position Rate

Left Inceptor = Longitudinal Position Rate or Speed Rate and Heading Rate or Sideslip

Fig. 9 Inceptor Configuration - 3

Predicted deficiencies for CC-3 arise from the lag introduced by the additional augmentation. This lag, given the less responsive handling characteristics of the LPC using differential RPM control in hover increases pilot workload and increases the likelihood of a PIO when not accompanied by a predictive display.

All of the novel inceptor configurations introduce the possibility of negative habit transfer (e.g. pulling up on the stick switches from a pitch response in forward flight to a heave response at low speeds) depending on pilot background.

F. AEP-1 Displays

The display concepts chosen for AEP-1 corresponded to the Command Concepts. This is best illustrated by the the navigation display hover guidance. All three concepts show a prediction of where the aircraft will end the deceleration. CC-1 and CC-2 use a green hover prediction line to indicate that the hover point is continuously computed to try to maintain zero groundspeed. CC-3 uses a magenta line with green hover circle to indicate that the hover endpoint is a commanded target using an earth referenced point (i.e., latitude and longitude) and the aircraft will continue to try to maintain that fixed point over the earth (Fig. 10). The difference becomes evident with differing environmental conditions, such as winds. If there are winds present, the CC-1 aircraft will drift with the winds unless the pilot corrects it. In CC-2 the aircraft will continuously attempts to maintain zero groundspeed, but will still drift in gusts, but the CC-3 aircraft will continue to return to the original hover target location.

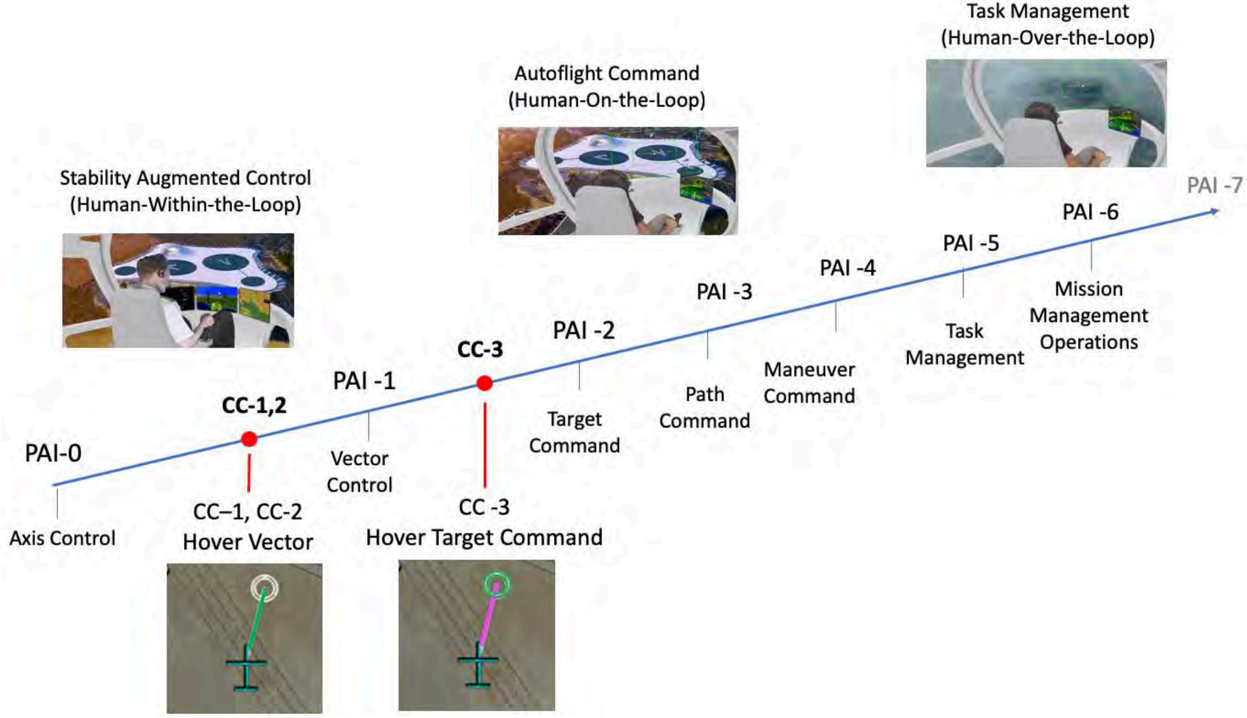


Fig. 10 Example Command Concepts Navigation Display difference (Hover Mode) in PAI framework

1. *Primary Flight Display*

The Primary Flight Display (PFD) was designed to meet the requirements for the Flight Test Maneuvers, but some consideration was given industry representative PFD design and capabilities available at the time of the AEP-1 study (e.g., synthetic vision). While the PFD display for CC-1 and CC-2 are largely similar, the PFD design for CC-3 provides information for speed, altitude, and direction targets as well as displays for the commanded targets on the Attitude Direction Indicator (ADI) including commanded Flight Path target cueing. The PFD is shown in Fig. 11.

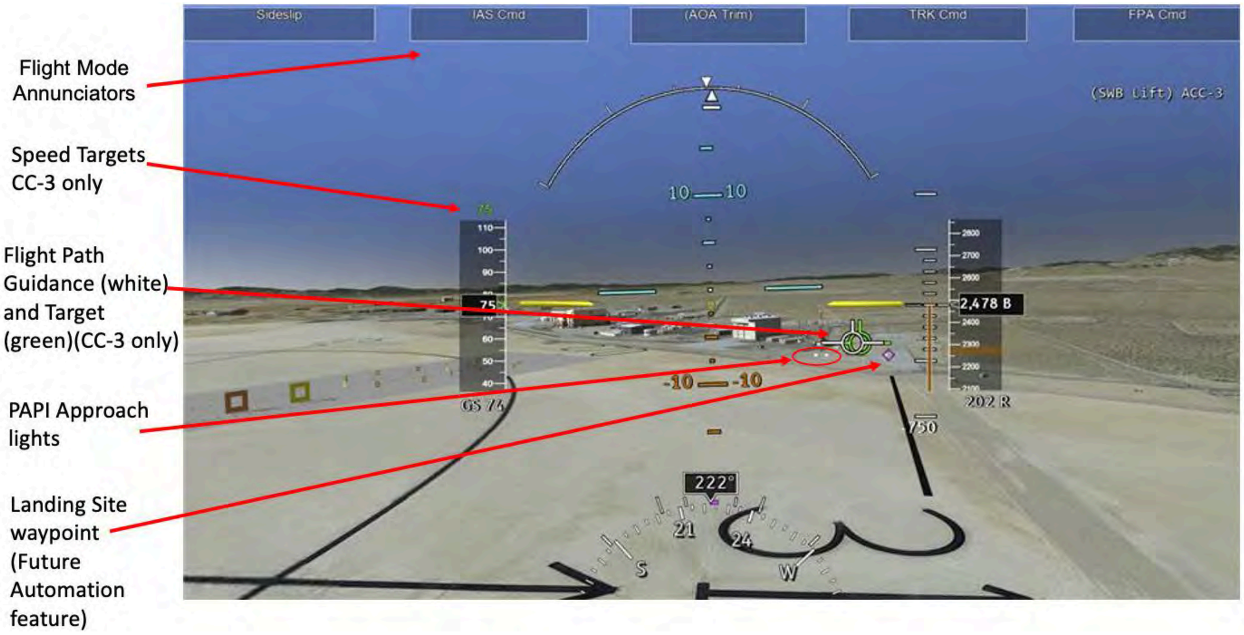


Fig. 11 AEP-1 Primary Flight Display (CC-3 configuration shown)

2. *Navigation Display*

Like the PFD, the Navigation Display uses a synthetic vision background to provide ground reference information. The display featured automatic map scaling during the AEP-1 study, although the automatic scaling could be overridden by participants if desired. An additional cue was added to highlight the point of intended landing from the long distances. An image of the Navigation Display is shown in Fig. 12

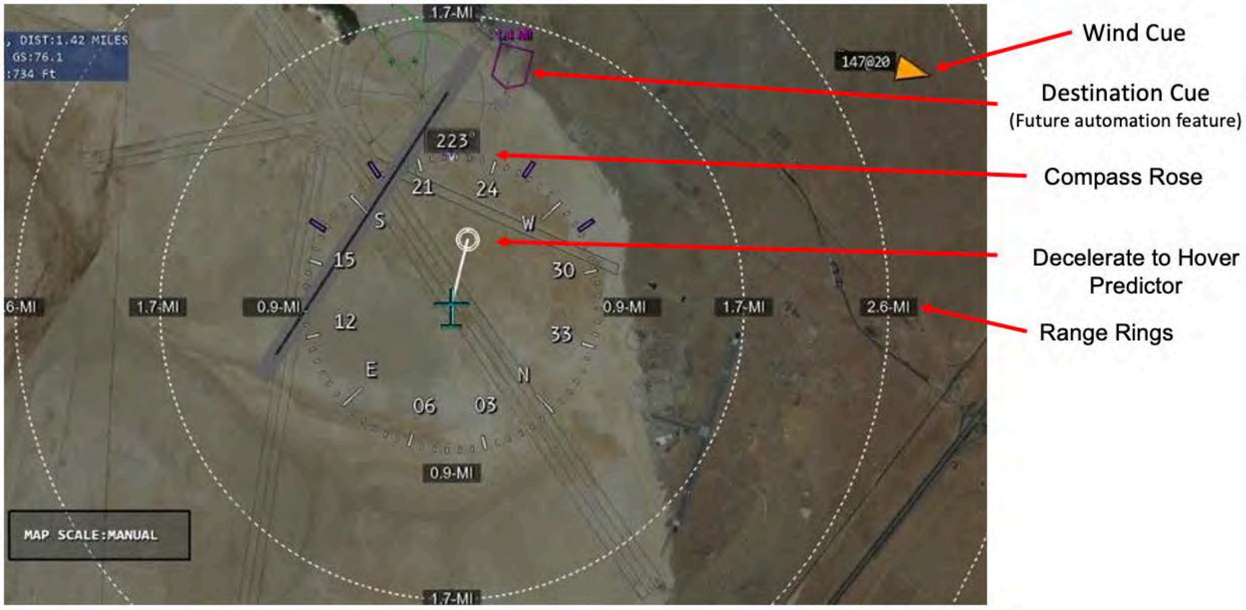
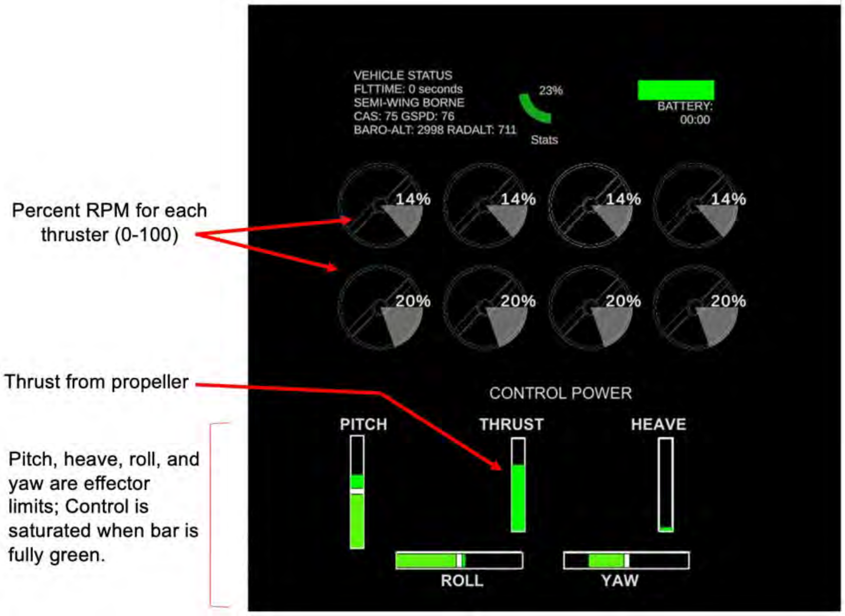


Fig. 12 AEP-1 Navigation Display (CC-1 shown)

3. *Secondary Display*

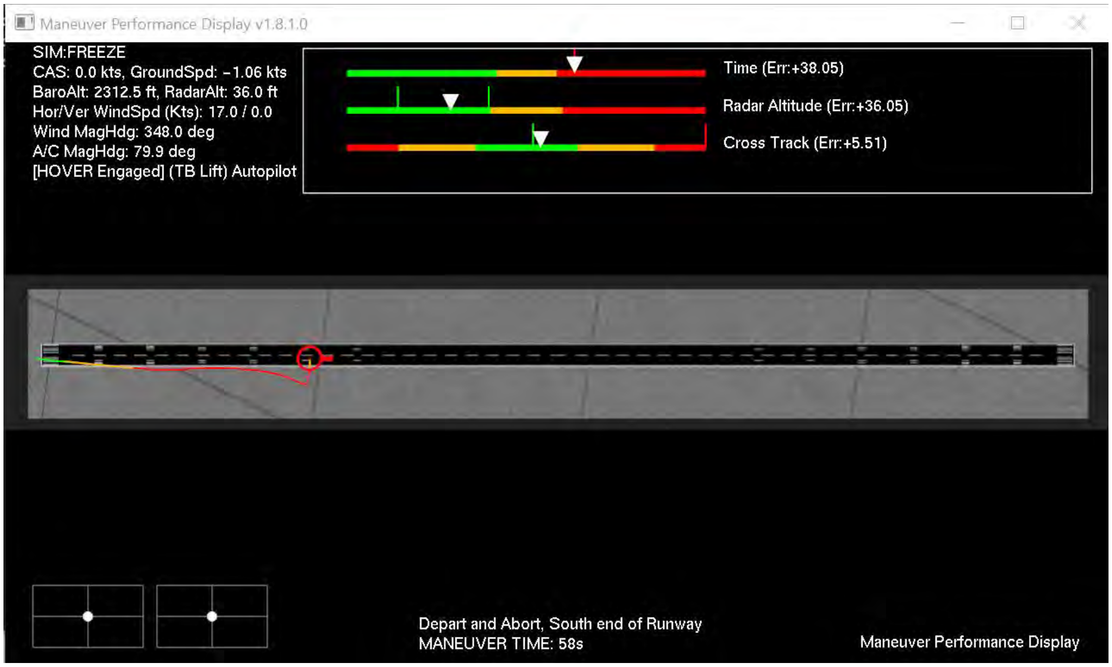
A secondary display was added to provide information regarding control saturation and energy usage. The display was available supported post flight analysis but was not used in real-time for the AEP-1 study.



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

4. *Maneuver Performance Display (MPD)*

A Maneuver Performance Display (MPD) was designed to mitigate an expected evaluation challenge. Many new V/STOL aircraft industry concepts depict a single pilot station configuration. This configuration would limit the view of the Flight Test Engineer (FTE) onboard the aircraft. Similarly, the chosen VMS R-cab configuration features a single pilot station configuration and the seating position for the FTE had a limited view of the test course and real-time aircraft data. The initial design of the display featured individual graphic depictions for each test maneuver the first study but was redesigned to a more universal design to allow selection of a variety of maneuvers. Different MPD depictions were created for each maneuver. An example is shown in Fig. 13.



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

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

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

Fig. 13 Maneuver Performance Display (Rejected Takeoff maneuver shown)

5. *Test Development*

The Flight Test Maneuvers development started with a review of previous Handling Quality Evaluation development efforts and requirements within NASA, the military, and the FAA. The focus of the effort was to develop a test range that exposed handling deficiencies expected with the proposed diverse set of industry aircraft concepts. Particular attention was given to deficiencies associated with transitioning between high speed and low speed flight which may include transitions between wing-borne and thrust-borne flight as well as transitions between airmass and earth referenced flight. The evaluation maneuver development effort included the development of measurable performance criteria and appropriate test range cueing that are representative of the proposed operational environment at the time of the study. The maneuvers, test course environment and performance criteria are provided as a starting point and are expected to change as the aircraft concepts and operational environment matures.

6. *AAM Operational Environment Assumptions*

The Mission Task Element approach is based on mission requirements for the aircraft under test. In civilian applications there is no requirement to specify a mission, so some assumptions were made about the expected operational concept and environment.

Assumptions regarding the dimensions of the approach course have been based on guidance from FAA Order [26], [United States Standard for Terminal Instrument Procedures (TERPS) [26]. Although the approach investigated in the study was tested as a VMC approach, the expectation that it should be designed to be applicable for instrument procedures expected in the future.

Most of the assumptions about the landing area are derived from FAA Advisory Circular 150/5390-2C [27]. The expected dimensions of the Final Approach and Takeoff Area (FATO) and Takeoff and Liftoff Area (TLOF) are based on the landing area for an equivalent rotorcraft.

7. *Flight Test Maneuver Overview*

The Mission – Task – Element (MTE) flight test maneuvers described in ADS-33E provided a basis for the Flight Test Maneuvers. A subset of the maneuver list is shown in Fig. 1 were selected for the initial catalog, based on relevance to the expected UAM mission and the ability to expose handling deficiencies in the proposed aircraft and automation concepts. The Pirouette and Slalom maneuvers are two examples of maneuvers that do not appear to have direct relevance to civilian AAM operational concepts but are efficient techniques for exposing handling deficiencies. The expectation is for the initial catalog to be extended and for individual maneuvers to be selected and tailored to suit the operational concept for the Type Certification applicant.

The list of maneuvers was further reduced due to the scope of the effort, as the research activity did not have resources to develop or mature models of aircraft performance or atmospheric effects. Examples include a lack of models for ground effect, density altitude, or dynamic interface resulted in excluding examination of Landing or Slope Landing maneuvers. It is expected that the maneuver descriptions and test cards would include these variations in flight test or as the models mature and become available in the future.

Immature operational concepts also limited investigation of some maneuvers. Based on the expected civilian operational concept, aggressive and tactical maneuvers were excluded from the initial test set as well as maneuvers relevant to tasks conducted in Degraded Visual Environment (DVE) and Instrument Meteorological Conditions (IMC). These maneuvers are expected to be investigated in subsequent studies as operational concepts mature. Examples include maneuvers conducted in response to hazard avoidance or for all-weather AAM operations.

Three maneuvers were selected from this reduced set for investigation of the Command Concepts, including:

- Precision Hover
- Rejected Takeoff
- Heliport Approach

The Precision Hover maneuver was chosen to highlight the effects of different levels of augmentation with the LPC handling characteristics. The Rejected Takeoff and Heliport Approach maneuvers were chosen to investigate the automation behavior during transitional flight.

G. Flight Test Maneuvers

1. *Precision Hover Flight Test Maneuver*

The Precision Hover Flight Test Maneuver is based on the ADS-33E maneuver of the same name. Minor modifications to the maneuver included a reduction in the stabilized hover time requirement and a removal of a requirement for no objectionable oscillations. The heading criteria was also relaxed based on a reduction in the Usable Cueing Environment (UCE) from the real world, despite additional cueing (e.g., hover boards). Some of the cueing furniture would need to be moved further from the aircraft to address safety concerns in real world flight test.

Multiple techniques are acceptable for accomplishing the 45-degree transition. If the aircraft is equipped with automation features (e.g., predicted hover, auto hover, etc.) the maneuver should be tested across the combinations of interventions (e.g., engagement, disengagement, recovery).

Table 4. Heliport Approach Flight Test Maneuver Description

Precision Hover

Task Objectives

- Check ability to precisely translate in longitudinal and lateral axes with mild aggressiveness.
- Check ability to maintain precise heading, and altitude while translating in the presence of a moderate wind from the most critical direction.
- Check for inceptor control harmony in all axes.
- Identify pilot-induced oscillation tendencies if present.
- Identify pilot workload for translating while maintaining ground track and speed to a stabilized hover and the ability to capture and maintain a precision hover.

Task Description

- Initiate the maneuver at a ground speed between 6 and 10 knots, and an altitude less than 20 feet. The altitude depends on the hover reference and the distance to the hover reference. The dimensions may be adjusted to achieve a desired hover altitude.
- The target hover point is a repeatable, ground referenced point from which aircraft deviations are measured.
- The target hover point should be oriented approximately 45 degrees relative to the heading of the aircraft, and the ground track should be such that the aircraft will arrive over the target hover point.
- The deceleration should be accomplished as one smooth maneuver, it is not acceptable to decelerate well before the hover point and then creep up on the final position.
- The pilot shall attempt to attain a stabilized hover within the specified performance times after the initiation of the deceleration.
- After capturing a stabilized hover, the pilot shall maintain a stabilized hover for 30 seconds while attempting to maintain the specified desired position tolerances.
- After capturing a stabilized hover, the pilot shall maintain a stabilized hover for 30 seconds while attempting to maintain the specified desired position tolerances. Repeat from adjacent corner of FATO.

Test Conditions

- Maximum permissible hover weight
- Visual Meteorological Conditions/Good Visual Environment
- Calm and moderate winds (e.g., 17 knots) from critical direction
- Light turbulence

Test Course Description

The target hover point shall be oriented approximately 45 degrees relative to the heading of the aircraft. The target hover point must be a repeatable, ground-referenced point from which aircraft deviations can be measured.

PRECISION HOVER EVALUATION CRITERIA

Performance Metrics	Desired	Adequate
Attain a stabilized hover position from start of deceleration within:	8 secs	12 secs
Maintain a stabilized hover for at least:	10 secs	10 secs
Maintain lateral-longitudinal position within:	+/- 3 ft	+/- 6 ft
Maintain altitude within:	+/- 2 ft	+/- 4 ft
Maintain heading within:	+/- 5 deg	+/- 10 deg

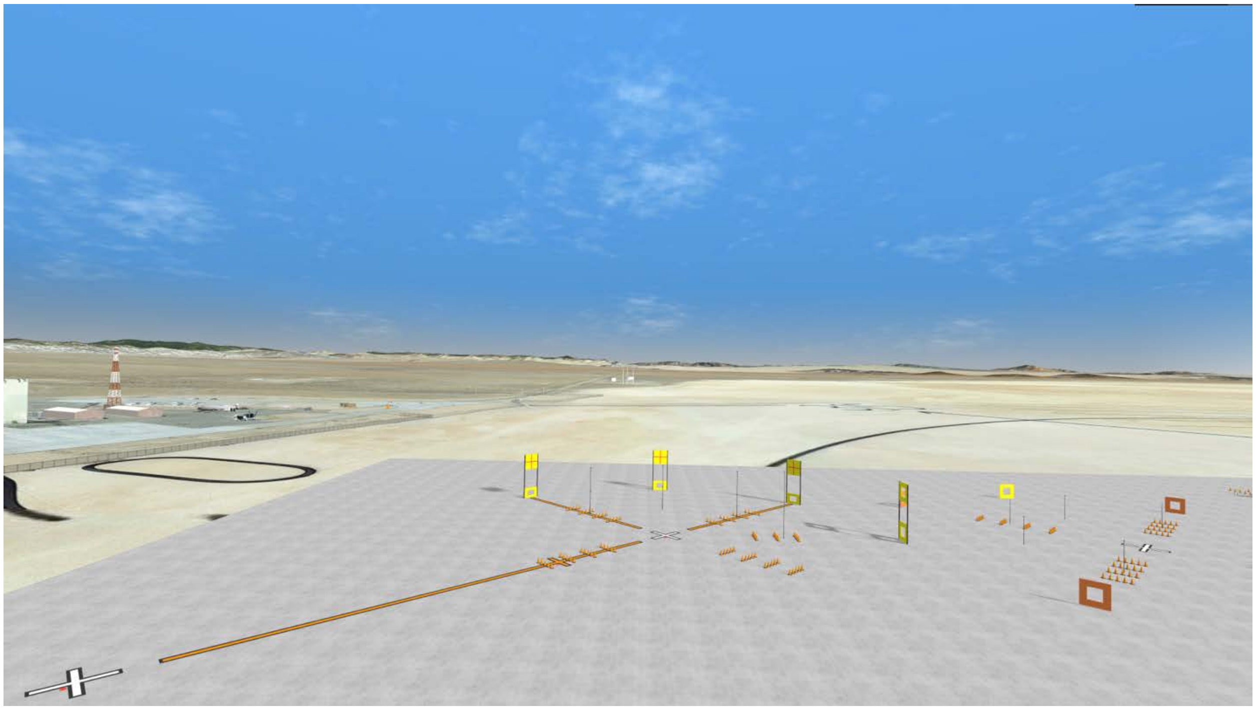


Fig. 14 Precision Hover Test Maneuver Test Course

2. *Heliport Approach Flight Test Maneuver*

The Heliport Approach is intended to be a limited agility maneuver, with an expectation that a variation would be used for Degraded Visual Environments (DVE) or Instrument Meteorological Conditions (IMC) in the future. Collaboration with a parallel research activity established the baseline and examined the approach with a helicopter Webber, D., "UAM Helicopter Surrogate Flight Test Report," AAM-NC-070-001, NASA, 2022. URL https://www.faa.gov/training_testing/testing/test_standards/.).

AEP-1 utilized the heliport approach procedure developed in FAAVE-1. The FAAVE-1 investigation revealed that the Lift Plus Cruise aircraft was limited to 8-degree approach at 70 knots with a minimum power command. Above 9 degrees the LPC was not capable of maintaining the glidepath. Based on data from previous powered lift testing [29] and initial testing of the two aircraft models, the 6-degree glide path at 70 KIAS was chosen as the initial approach profile. AEP-1 tested only the 6-degree glidepath angle using a calm wind condition and a condition with a 17-knot crosswind.

For AEP-1 the performance of the approach was evaluated in two segments. The initial approach segment, consisting of centerline and glide path capture, was flown under wing-borne flight conditions where actuators retained their effectiveness. Therefore, performance during this portion was expected to be adequate. The final segment begins as the pilot initiates deceleration and ends at the FATO boundary. The final segment deceleration was predicted to be the more challenging of the two segments.

The AEP-1 configured aircraft allowed manual arming or engagement of the Hover Mode based on results from prior investigations with automatic transition to hover mode. While all these updates improved handling and behavior, the results still illustrated challenges in performance with this vehicle design.

This study investigated requirements for the approach including the avoidance of predicted aircraft performance constraints (e.g., adequate control margin, Height-Velocity Avoid areas, etc.). The investigation also examined requirements for the approach profile across a range of consideration including the desire to minimize time in thrust-borne flight, land in confined landing areas, minimize external noise footprint and maintain acceptable ride quality.

A 17-knot crosswind was used to expose handling deficiencies associated with transitions to low-speed maneuvering, particularly the transition from a crab to a sideslip to allow observability of the landing area during the final segment of the approach.

Three different Visual Glide Slope Lighting Indicator (VGSI) systems were tested. The Pulsating Light Approach Slope Indicator (PLASI), the Improved Fresnel Lens Lighting System, (IFLOLS), and the Precision Approach Path Indicator (PAPI). Although every effort was made to improve the lighting characteristics of the simulated VGSI systems, no analysis was conducted to determine the characteristics relative to a simulated day Usable Cue Environment (UCE).

Table 2. Heliport Approach Flight Test Maneuver Description

HELIPORT APPROACH

Task Objectives

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

Task Description

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

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

Test Conditions

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

Test Course Description

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

EVALUATION CRITERIA

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

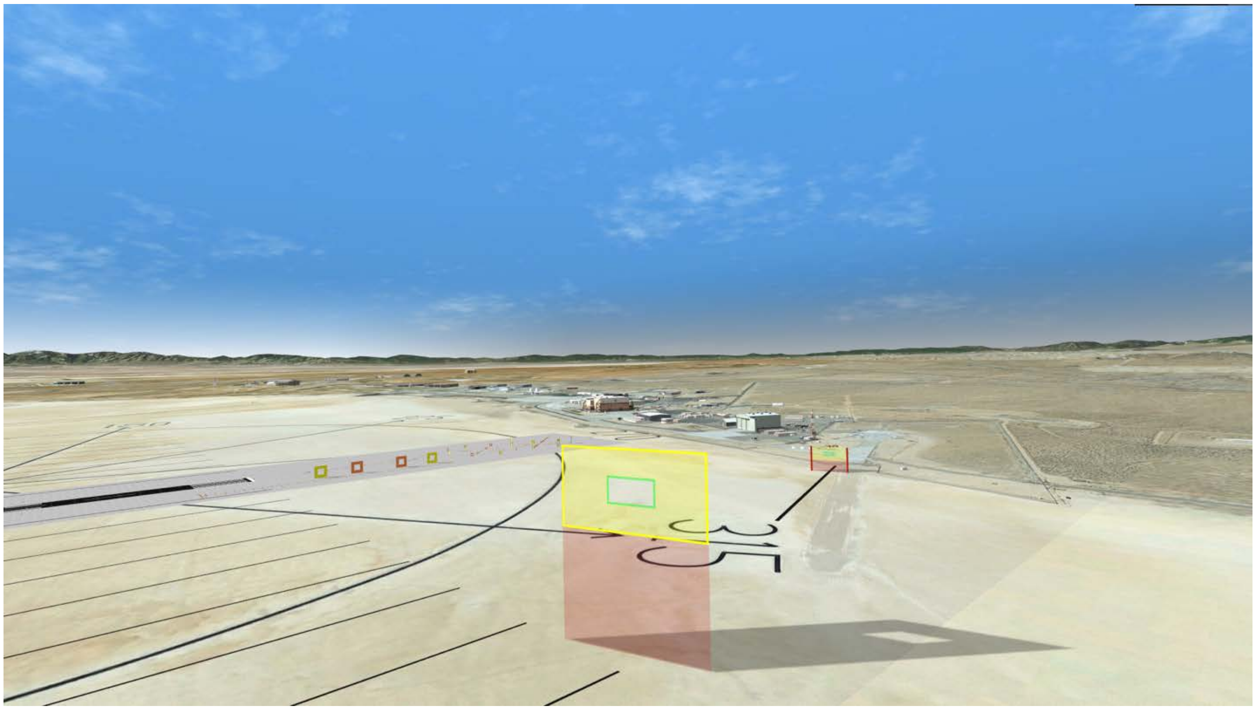


Fig. 15 Heliport Approach Course with Performance Boards

3. Rejected Takeoff Flight Test Maneuver

The Rejected Takeoff maneuver is a revision of the Depart/Abort maneuver examined in FAAVE-1. The maneuver consists of a rapid acceleration followed by rapid deceleration, highlighted mode transitions and aerodynamic changes, particularly focused on exposing lateral control challenges. The test course of the maneuver was lengthened to expose any deficiencies with control associated with the transition from thrust-borne to wing-borne flight and adjusted based on considerations of future evaluation performance of multi-engine aircraft (e.g., 14 CFR 29 Category A, §23.2135) [30, 31].

The Critical Decision Point (CDP) speed of 80 KIAS is a function of stall speed for the LPC aircraft model and assumes no autorotation capability. The CDP target speed should be adjusted as necessary to transition through lift modes, reference frames and/or configuration changes that would affect controllability during takeoff.

Table 5. Rejected Takeoff Flight Test Maneuver Description

Rejected Takeoff
Task Objectives • Check precision control of the aircraft under maximum acceleration and deceleration conditions. • Check for any undesirable coupling between the roll, pitch, yaw, and heave axis controllers. • Check for harmony between the pitch axis and heave axis controllers. • Check for any undesirable behavior introduced across transitions (e.g., Lift-Modes, Command modes/functions, Response types, Reference Frames, Flight Envelope Protections). • Check for any undesirable inceptor design characteristics, including control forces and displacements. • Identify pilot-induced oscillation tendencies if present. • Check for overly complex power management requirements.
Task Description • From a stabilized hover, initiate a longitudinal acceleration to perform a normal takeoff. • After accelerating to the Critical Decision Point (CDP) speed (e.g., 80 KIAS), abort the takeoff at the maximum deceleration rate.

- The acceleration and deceleration phases shall be accomplished in a single smooth maneuver.
- The maneuver is complete when control motions have subsided to those necessary to maintain a stable hover.

Task Variations

- The maneuver shall be performed in calm wind and moderate wind conditions with the wind from the most critical direction.
- There may be multiple methods for commanding and aborting the takeoff.
- Altitudes may need to be adjusted for aircraft configuration limits.
- Aircraft should initiate maneuver from takeoff position, on ground or hover.

Test Course Description

The minimum test course shall consist of a reference line on the ground indicating the desired track during the acceleration and deceleration. The course should include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate lateral tracking performance.

EVALUATION CRITERIA

HQ PERFORMANCE METRICS	**Desired**	**Adequate**
Maintain lateral track within:	+/- 20 ft	+/- 50 ft
Maintain altitude below:	50 ft	75 ft
Complete deceleration within:	25 secs	35 secs
Complete maneuver along runway heading within +/-:	+/-10 deg	+/-15 deg
Any inter-axis coupling, oscillations or behavior across transitions shall not be:	Undesirable	Objectionable

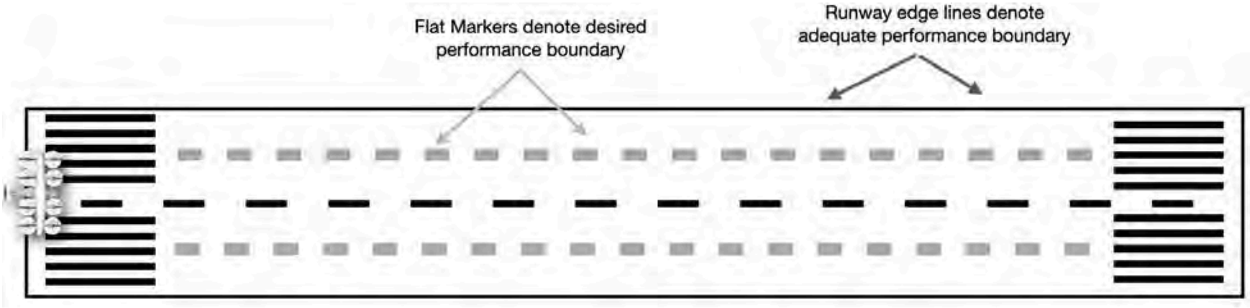


Fig. 16 Rejected Takeoff Test Course (Top View

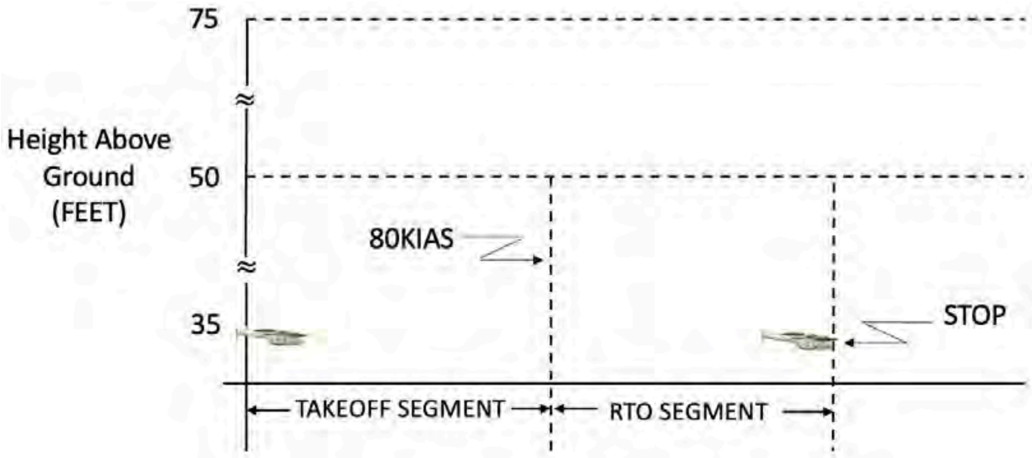


Fig. 17 Rejected Takeoff Test Course (Profile View)

Fig. 18 Rejected Takeoff Initial Condition

VI. Simulation Development

The development work for the studies was performed with an internally developed simulator environment referred to as FlightDeck Z. FlightDeckZ includes representative aircraft model(s), applicable flight guidance systems, automation capabilities and connections to pilot interfaces (i.e., displays and inceptors). The aircraft simulation components, external visual environment, test course and test materials were developed in part-task and in the Aerospace Cognitive Engineering Lab – Rapid Automation Test Environment (ACEL - RATE) simulator. Once developed, the simulation environment was then moved to NASA Ames Vertical Motion Simulator (VMS) for high-fidelity simulation testing.

Both FAA V/STOL Evaluation studies utilized the same development approach, capabilities, and facilities. The development used the internally developed NASA FlightDeck Z simulation capabilities for aircraft performance.

The NASA FlightDeck Z simulation environment consists of three main components:

1. **Flight Z** can import aircraft performance models in different formats provides capabilities for modeling and integrating aircraft performance and with flight controls.
2. **FMS Z** provides flight management system functionality (e.g., trajectory generations, flight plan navigation and editing) and advanced automated capabilities (e.g., auto-takeoff, auto-land, etc.).
3. **Deck Z** provides user interfaces for development and part task testing.

The NASA Flightdeck Z simulation capabilities are modular and portable to different simulation hardware environments. The studies utilized three different environments developed as part of NASA research activities and adapted for the development of the FAA studies. The hardware configurations included a low fidelity part-task environment, a medium fidelity simulator and a full mission, high fidelity simulator.

A. Low Fidelity part-task simulation environment

The low fidelity part-task environment (e.g., laptop, desktop) environment was used for initial development. The intended use of the low fidelity environment was for low level software function development., however the environment was significantly expanded due to heavily restricted access to the ACEL-RATE and VMS simulators during the Covid-19 pandemic. This led to the development and addition of representative pilot interfaces and Out-The-Window visual displays.

B. Medium Fidelity Fixed-Base simulator

The Aerospace Cognitive Engineering Lab – Rapid Automation Test Environment (ACEL-RATE) simulator was used for initial testing and validation. The studies used identical display hardware in the ACEL–RATE and VMS simulators, consisting of a Primary Flight Display, Navigation Display (i.e., Map) with a look down camera capability, systems health displays and floor mounted displays to provide a view of the aircraft height above terrain. The Out the Window visual database was developed in the ACEL-RATE lab and used in the VMS, however the OTW display hardware utilized differed. ACEL-RATE consists of a 200-degree Field of View screen in front of reconfigurable cockpit hardware (Fig. 19).

Fig. 19 ACEL-RATE simulator

The ACEL-RATE cockpit configuration assembled for the studies replicated the dimensions of the VMS pilot station. An image of the pilot station is shown in Fig. 20.

Fig. 20 ACEL-RATE simulator pilot station

C. High Fidelity Motion Simulator

The NASA Ames Vertical Motion Simulator (VMS) (https://www.nasa.gov/ames/vms) provided the high-fidelity simulation capabilities for studies. The VMS facility utilizes several different cabins configured for different classes of vehicles. The studies described in this report utilized the "R-cab" configuration, which is configured for a single pilot station at the center of 3 Out-The-Window displays with a 130-degree Field of View (FOV). The R-cab configuration was chosen to be representative of leading industry cockpit configurations and explored the potential challenges in observability of maneuver performance by the Flight Test Engineer. The VMS simulation used FlightDeck Z for the aircraft performance and automation engine, and utilized displays developed in the ACEL-RATE simulator including the Out the Window visuals. A software architecture was developed for the studies to enable software updates to be rapidly sent from the ACEL-RATE simulator and integrated with the VMS hardware.

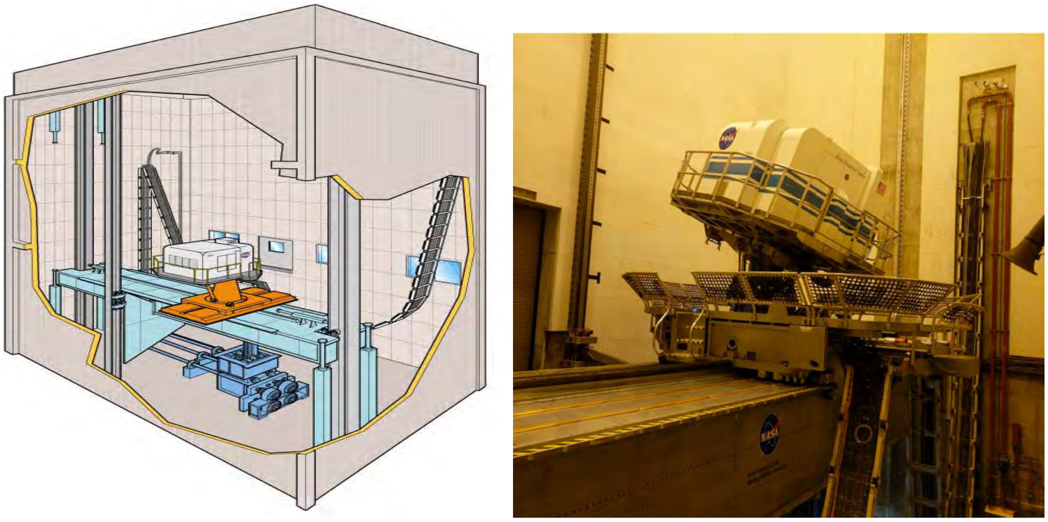


Fig. 21 Vertical Motion Simulator (VMS)

Fig. 22 VMS R-Cab Pilot Station with maneuver performance display behind pilot

4. *Test Course*

A simulated test course was constructed and placed in simulated representation of the U.S. Air Force Edwards Air Force Base and NASA Armstrong Flight Research Center (AFRC). The development of the test course was informed by previous test courses at NASA Ames Research Center at Moffett Field, CA and the U.S. Naval Test Pilot School at Patuxent River, MD as well as collaboration with parallel test course development at AFRC in conjunction with a NASA National Campaign activity. The simulated visual environment included depiction of terrain and many buildings compromising the Edwards Air Force Base complex. The location was chosen to correspond to certain elements (e.g. heliport approach landing zone) of a test course constructed in the real world at NASA AFRC. The simulated low speed and hover test course was placed in an unused portion of Rogers dry lake for proximity to the other components of the test course. The test course has been designed in a virtual environment in Open Flight 3D geometry model format. A view of the approach course and low speed and hover test course is shown in Fig. 23Fig. 24Fig. 25.

Fig. 23 Image of virtual test course, seen from Heliport Approach. The low speed and hover test course can be seen on the left.

Fig. 24 Image of the low speed and hover course from, looking east through the PFD

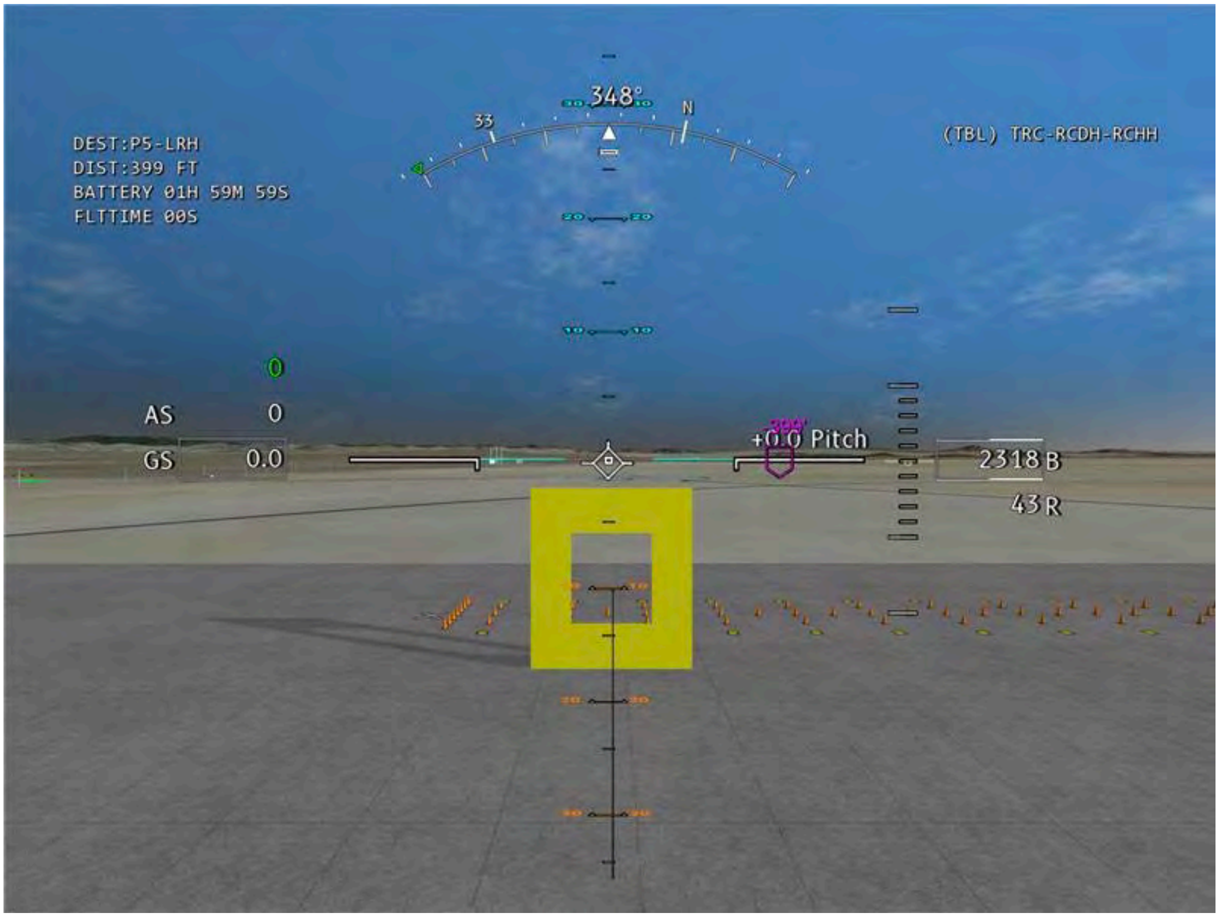


Fig. 25 Illustration of a Hover Board through the PFD

VII. Automation Enabled Pilot (AEP – 1) Study

AEP-1 tested three industry representative automation concepts referred to as Command Concepts (CC) -1, -2 and -3. The Command Concepts integrated flight controls and pilot interfaces (e.g., inceptor configurations). Three maneuvers, the Precision Hover, Heliport Approach and Rejected Takeoff were evaluated. Each of the three maneuvers were tested in calm winds and with a 17-knot wind from the most critical direction.

The study was designed such that training was conducted in the ACEL-RATE simulator the day prior to testing in the VMS. During training, each of the different concepts the day were introduced and trained with aircraft familiarization training as well as training for individual maneuvers. The testing was conducted in the VMS over one day and the schedule was designed with breaks and familiarization between the different Command Concepts. AEP-1 also tested a new performance evaluation displays and configuration that were later used in FAAVE – 2.

The participants for AEP-1 consisted of 6 formally trained test pilots with VTOL and powered lift flight experience. Four of the test pilots had a majority of experience with fixed-wing aircraft and two had a majority of flight experience in rotary wing aircraft. Data Collection for AEP – 1 was conducted in the VMS in February 2022.

VIII.Results

Full test matrix data (three Command Concepts, three Flight Test Maneuvers, two wind conditions) was collected from five of the six participants. One participant completed two of the three Command Concepts, resulting in 102 data runs. Overall participant feedback highlighted that the maneuvers could find deficiencies associated with the combination of aircraft, Command Concept and pilot interfaces. Each of the maneuvers also had at least one participant capable of achieving desired performance, however feedback from the pilots identified automation combinations that resulted in unpredictable aircraft behavior or unacceptable pilot workload.

1. Precision Hover

The results for the Precision Hover maneuver conducted in AEP-1 are shown in Fig. 26 with desired (green) and adequate (amber) performance gates marked for clarity. Performance ranged from desired to adequate. As hover mode uses ground reference controls, the addition of crosswind was not expected to be a factor. Results in performance and ratings confirms this behavior.

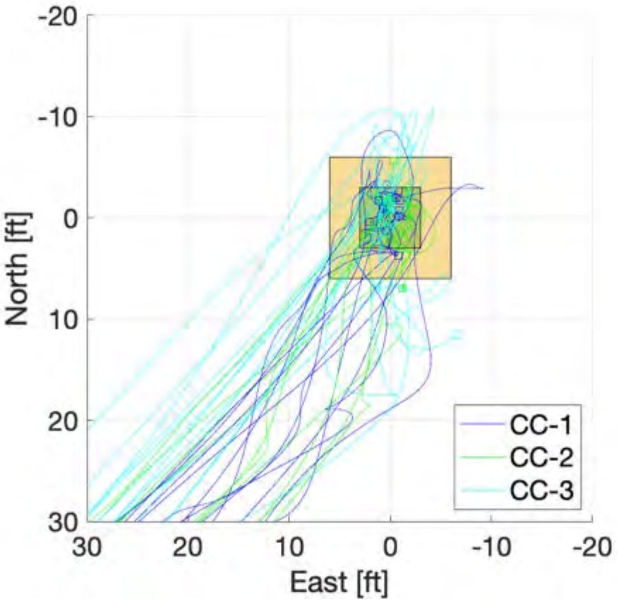


Fig. 26 Precision Hover Command Concept performance

Command Concept-3 (CC-3) uses increased automation such that a pilot commands a hover target, which slows the aircraft response to pilot inputs. The corresponding reduction in handling characteristics can result in a tendency to overshoot the hover target as illustrated Fig. 26 and highlighted a need for a predictive display for accurate positioning. Even with the predictive display, the sluggish aircraft response produced Pilot Induced Oscillations as shown in the time lapse view of the navigation display (Fig. 27).

Some pilots were asked to perform this task both with and without looking at the map. As seen in Fig. 28b, performance the predictive display was adequate (CHR Level 2) and without the predictive guidance the overall performance was inadequate (CHR Level 3). Some pilots reported that it was not possible to meet the performance criteria without using the display. Although the addition of map guidance resulted in better performance and ratings, further investigation is required to determine the implications of using a display that divides the pilot attention between the outside world and a cockpit display.

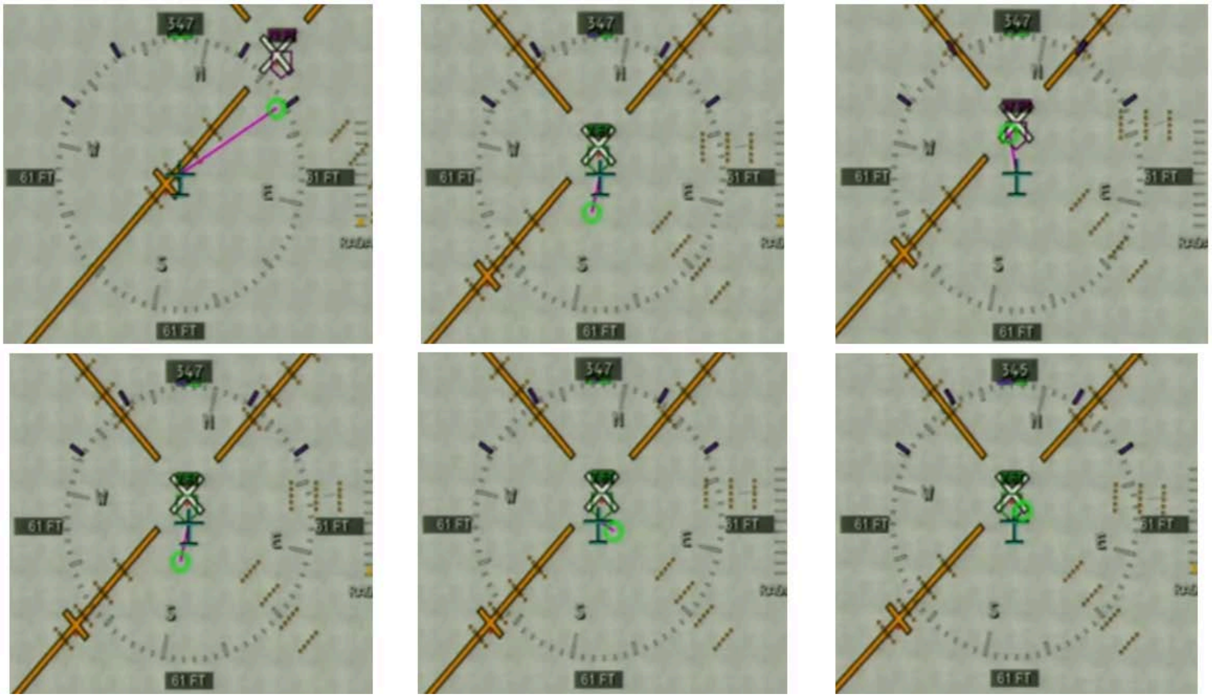
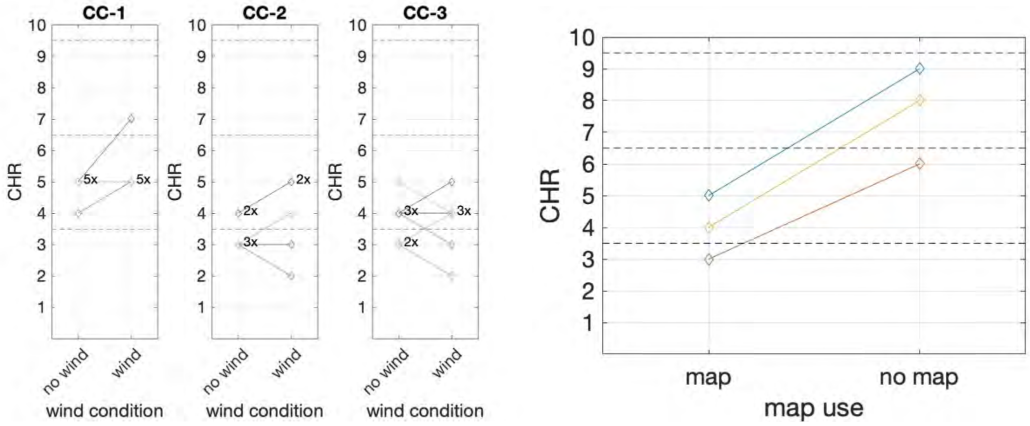


Fig. 27 Example of CC-3 target and aircraft oscillation over 25 second time span



(a) Comparison over wind and control concept (b) Comparison over map use for CC-3

Fig. 28 Cooper-Harper Ratings for Precision Hover

The test pilots felt that the precision hover is a good maneuver for identifying control harmony in multiple axes. The test course was slightly modified to provide additional visual cueing. Additional test course visual cueing environments (e.g., furniture) were added, to increase the Usable Cueing Environment to be closer to the real world.

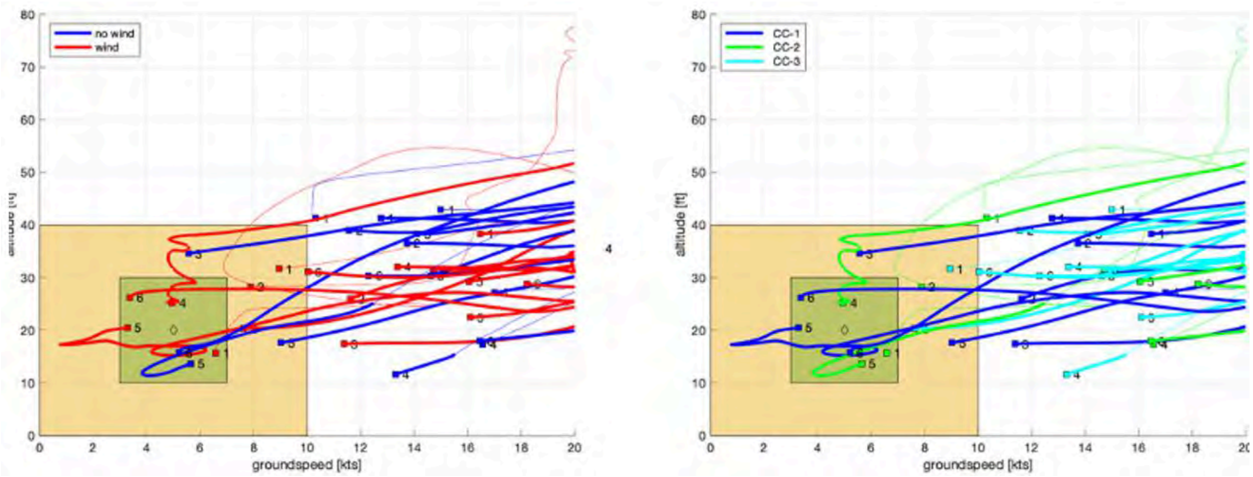
The feedback and data from the testing of the maneuver with multiple aircraft and automation configurations confirmed that the Precision Hover maneuver is useful in finding handling deficiencies for novel V/STOL configurations.

2. Heliport Approach

The pilot ratings for the Heliport Approach confirmed expectations that the final segment would be more challenging. Nearly all pilots met desired performance criteria for the initial segment at the 200’ gate crossing, under all command concepts (not shown). Observation of the maneuver revealed that a lack of visual references combined with tight speed and altitude tolerances may have contributed to the apparent gap between the flight technical data and what was observed.

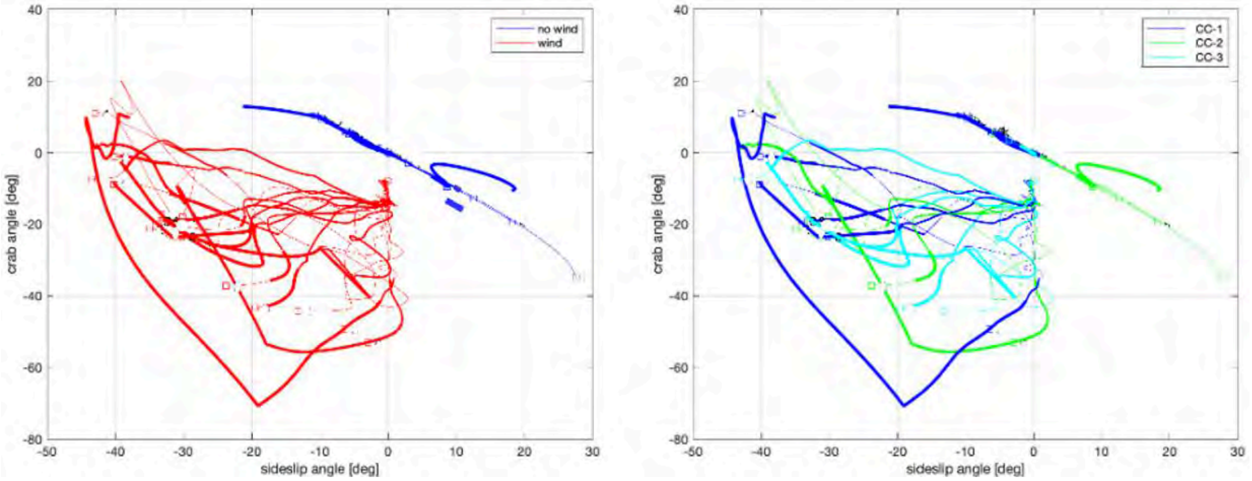
The participants stated that the PAPI was the most useful of the systems in the simulation. The simulated PLASI and IFLOLS did not provide enough relative luminance in the simulated day environment and could not provide useful guidance in the initial segment. In addition, PLASI did not provide as much information about aircraft trend in regard to glidepath as the other two systems.

The performance for the final segment Heliport Approach without wind ranged from desired to outside of adequate as shown in Fig. 29 and 29 with desired and adequate performance at the FATO threshold marked for clarity. Closer inspection, however reveals that while many of the endpoints of the approach maneuver ended outside of adequate performance, the range of performance largely remained consistent.



(a) Comparison over wind (b) Comparison over command concept

Fig. 29 Heliport Approach Trajectories



Computed Calibrated Airspeed >10 knots

(a) Comparison over wind (b) Comparison over command concept

Fig. 30 Heliport Approach Crab Angle to Sideslip Transition

Performance ranged from adequate to outside of adequate when wind was added to the Heliport Approach. Flight technical data and pilot feedback confirmed that the largest contributor to performance outside of adequate was a lack of yaw control as the LPC aircraft transitioned from a crab to a sideslip. The deficiency presented either a loss of yaw control or an overspeed as the pilots attempted to retain control. The participants commented about the deficiency although provided different explanations. The participants rated the transition from a crab to a sideslip with particularly poor ratings, remarking about the loss of control. One participant explained after achieving desired performance that he wasn't sure how he did it and didn't think he could repeat it.

These results and pilot feedback demonstrated a predicted handling deficiency with the LPC. The results also illustrated that the visual glidepath indications would need modification for subsequent studies as participants had difficulty determining the tightly constrained desired or adequate performance for the approach while looking out the window.

3. *Rejected Takeoff Results*

As the vehicle accelerated it tended to point into the wind and a lack of directional authority. Pilots who added sideslip to keep the noise pointed down the centerline, eventually encountered rudder saturation as the stabilizing yaw moment produced by the vertical tail exceeded the control power of the rudder. Similarly, throughout deceleration, lateral corrections resulted in rudder saturation as effectiveness was lost at decreasing airspeeds and lifting propulsors were slow to compensate. Across all control concepts, several lateral PIOs were encountered as pilots applied aggressive lateral corrections to keep the track aligned with the runway centerline.

Fig. 32 a and b show study results, with and without wind respectively, where medium thickness lines indicate deceleration phase and maximum thickness indicates that hover mode was active.

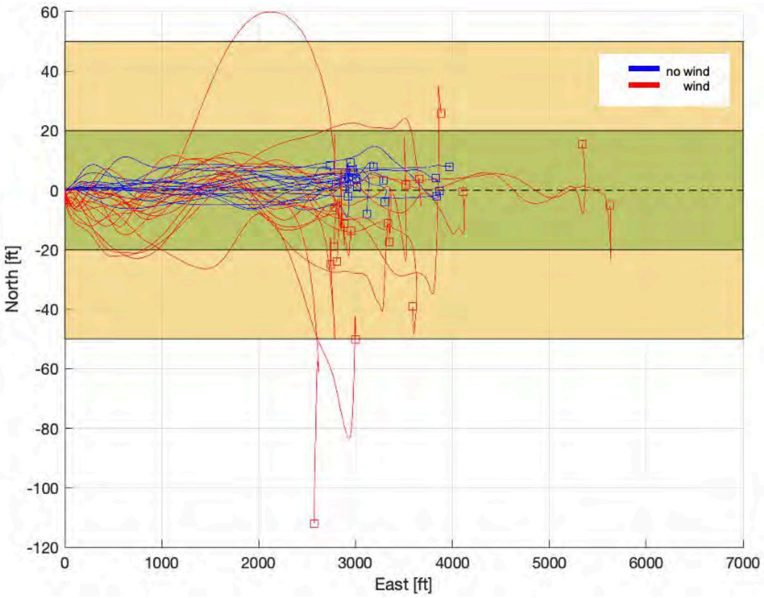
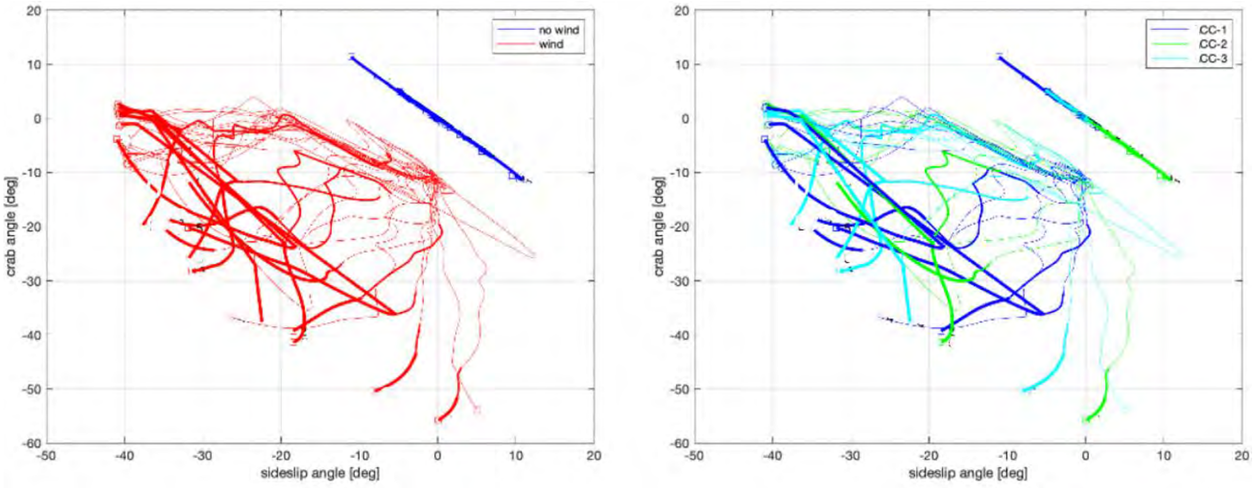


Fig. 31 Rejected Takeoff lateral deviation



Computed calibrated airspeed > 10 kts

(a) Comparison over wind (b) Comparison over command concept

Fig. 32 Rejected Takeoff Crab to Sideslip Transition

As expected, wind had a dramatic effect on performance. Overall, with wind, improvements gained in the higher command concepts could not compensate for vehicle performance limitations. Participants commented that the maneuver was very different with and without winds.

Mode transitions caused added challenges. Through deceleration, constant pedal inputs to decrab would eventually cause the vehicle to yaw as the command response type transitioned from Sideslip Command to Heading Rate Command, contributing to veering off the centerline.

Additionally, it appears that some Biodynamic Feedthrough (BDFT) [32] or Rotorcraft – Pilot Control Coupling (RPC) [33] may have adversely affected performance even in the no wind condition as the aircraft was continuously accelerating and decelerating longitudinal along with almost constant lateral accelerations. These effects were not examined in detail and would require further investigation.

IX. Conclusion

This paper described a research activity aimed at developing evaluation methods that accommodate a range of automated aircraft systems (i.e., pilot on-onboard, remotely operated or autonomous) and a diversity of aircraft configurations expected for Advanced Air Mobility (AAM). AAM has a special focus on aircraft with electric propulsion and Vertical Takeoff and Landing (eVTOL) capabilities expected, and the research activity has a specific focus on automation technologies for these aircraft and operational concepts.

The research required the development of industry representative aircraft system concepts and evaluation infrastructure (e.g., eVTOL aircraft models, automation, procedures and urban scenery databases for visual systems, scenarios, etc.) used to support the development of evaluation methods for eVTOL aircraft and automation concepts and results from a simulator study to examine the efficacy of flight test maneuvers. While industry AAM aircraft concepts are diverse, the current focus includes onboard pilots reflecting the state of the industry until the concept of operations mature to the point to allow remote piloting or autonomous operations. During development improvements were repeatedly made to improve the aircraft, controls, and simplified command concepts. Even with the improved behavior vehicle deficiencies are predicted and environmental conditions expected for operations can push the vehicle near control authority limits.

Interest was placed on developing materials to support assessment of piloted eVTOL aircraft with Indirect Flight Control Systems (IFCS), reflecting the state of the leading industry airworthiness applications and FAA needs. IFCS require design decisions about desired behavior as the aircraft transitions from forward flight to low speed or hover. IFCS also enable aircraft applicants to deviate from conventional pilot station configurations (e.g., cyclic, and collective inceptors, pedals). Some of these transitions occur regardless of aircraft configuration (e.g., airmass to ground-referenced flight, envelope protection) while others (e.g., the transition from wing-borne to thrust-borne flight) will vary with aircraft configurations (e.g., Tilt-rotor, Tilt-Wing, Lift Plus Cruise, etc.).

A new framework referred to as the Pilot-Automation-Interaction (PAI) framework was developed to help describe the complex combinations of aircraft, automation, and interface capabilities. The framework provides a roadmap of evolutionary automation capability development to aid in highlighting evaluation areas of interest with specific combinations of capabilities and was used to describe the combinations developed and evaluated as part of the NASA Automation Enabled Pilot study -1 (AEP-1).

The AEP-1 study one of a series of studies funded by NASA and the FAA to establish Flight Test capabilities (e.g. Maneuvers, test courses, instructional materials), for a variety of uses, including support for the development of a Means of Compliance for certification of novel AAM aircraft and automated concepts. The maneuvers are intended to be operationally representative. focused on the assessment of various automation configurations using one industry representative aircraft concept and expected flight test maneuvers. AEP - 1 provided and opportunity for development and validation of simulation resources including updates to the aircraft performance models, pilot interface, test course infrastructure and flight test performance displays.

The initial research efforts adapted an evaluation methodology used by the military for assessing VTOL capable aircraft flying and handling qualities against mission requirements referred to as U.S. Army Aeronautical Design Standard 33. The initial research efforts validated the use of the MTE approach described in ADS-33 as useful framework for evaluating different levels of automated systems on aircraft and assessing the wide variety of novel AAM aircraft configurations being proposed. The Flight Test maneuvers developed from the research effort are intended to be a starting point for a new Means of Compliance for the evaluation of handling qualities for the new Powered Lift class of aircraft. The maneuvers are intended to stress the handling qualities of the aircraft to expose deficiencies, but the associated performance criteria were designed to align with the expected requirements of AAM operations and infrastructure. The research successfully produced and assessed an initial set of maneuvers, performance criteria and test course specifications applicable to AAM operations.

The methodology also highlights the requirement to clearly define operational concept details to precisely define maneuver performance requirements. The definitions and an understanding of the operational environment are critical to successful automation design and evaluation also relies upon accurate definition of the mission objectives and an understanding of the operational environment. It is hoped that a “mission-based approach” will also help manage the diversity in automation approaches by providing a connection between flight test of automated aircraft and system safety evaluation. While there are instances of the use of mission related details included in aircraft certification category definitions and some regulatory material, these are mostly limited to transport category aircraft and rotorcraft (§25.1302, §25, 29.1301). Most existing analyses (§23,25, 27, 29.1309) focus on the likelihood and severity of identified “failures” which may be inadequate. Automated systems may “fail” in non-traditional ways, if the system does not account for all operational situations encountered. Correspondingly, a lack of maturity of proposed operational concepts presents a challenge. It is the intention of a mission-based assessment method to focus on accurate definitions of operational concepts and associated performance criteria to assure the target level of safety and accelerate AAM operations.

Future work will focus on development of the evaluation methods as AAM concepts and corresponding performance requirements mature. It is hoped that the initial candidate maneuvers, methodology and framework will support assessment of the wide diversity of novel proposed aircraft and automation configurations and provide a starting point for future development.

Acknowledgments

The authors wish to thank the Airspace Operations and Safety Program’s Advanced Air Mobility project and FAA agreement 692M15-19-N-00010 for funding this work. The authors would like to acknowledge the support of John Archdeacon, Nelson Iwai, and NASA Ames Vertical Motion Simulator (VMS) staff Steve Norris and Edgar Torres. Many FAA colleagues were vital to the development of this project, particularly David Sizoo, David Webber, Mitch Soth, Jon Jordan, and Ross Schaller,

References

[1] FAA, 2023, “Urban Air Mobility and Advanced Air Mobility”, https://www.faa.gov/uas/advanced_operations/urban_air_mobility [retrieved April 17, 2023].

[2] National Aeronautics and Space Administration, “Advanced Air Mobility Project”, https://www.nasa.gov/aeroresearch/programs/aosp/aam [retrieved April 27, 2023].

[3] Anon., “Handling Qualities Requirements for Military Rotorcraft”, Aeronautical Design Standard ADS33E-PRF, U.S. Army Aviation and Missile Command, Mar. 21, 2000.

[4] Blanken, C., Tischler, M. B., Lusardi, J. A., Berger, T., Ivler, C.M. and Lehmann, R. Proposed Revision to Aeronautical Design Standard – ADS33E (ADS-33e-PRF) Toward ADS-33F-PRF, Special Report FCDD-AMV-19-01, September, 2019.

[5] 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.

[6] Kaneshige, J., Lombaerts, T., Shish, K., and Feary, M., "Command and Control Concepts for a Lift Plus Cruise Electrical Vertical Takeoff and Landing Vehicle," AIAA AVIATION 2023 FORUM, American Institute of Aeronautics and Astronautics, 2023, submitted for publication.

[7] 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.

[8] McElroy, C. E., "FAA Handling Qualities Assessment – Methodology in Transition", presented at 1988 Society of Experimental Test Pilots Symposium.", Anaheim, CA, 1988.

[9] FAA, Certification Procedures for Products and Articles, US Code of Federal Regulations 14 CFR 21, (https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-21)

[10] Ivler, C. M., Russell, K., Gong, A., Berger, T. and Lopez, M. J. S. Toward a UAS Handling Qualities Specification: Development of UAS-Specific MTEs. Presented at the Vertical Flight Society's 78th Annual Forum & Technology Display, Ft. Worth, TX, USA, May 10-12, 2022.

[11] Federal Aviation Administration, Performance-Based Operations Aviation Rulemaking Committee, FAA Order 1110-139, February 2004.

[12] Sheridan, T. B., & Verplank, W. L. (1978). "Human and computer control of undersea teleoperators". Massachusetts Institute of Technology Cambridge Man-Machine Systems Lab.

[13] Society for Automotive Engineers, "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Vehicles," SAE Surface Vehicle Recommended Practice, April 2021, SAE J3016_202104. https://www.sae.org/standards/content/j3016_202104

[14] Rasmussen, J. "The role of hierarchical knowledge representation in decision making and system management. IEEE Transactions on Systems, Man and Cybernetics, 15, 234-243, 1985.

[15] Rasmussen, J., Concepts, and structures in models of human process operators. Electronics Department, Riso National Laboratory. Technical Report NKA/KRU-P2(79)14, 1979

[16] Feary, M. "A Decomposition Framework for Describing Advanced Air Mobility Missions Functions", AIAA Aviation Forum, June 15-19, 2020, Virtual Event.
doi: 10.2514/6.2020-3249

[17] Landis, K. H. and Glusman, S. I. Development of ADOCS Controllers and Control Laws Volume 3 Simulation Results and Recommendations, NASA Contractor Report, NASA-CR-177339-Vol-3), Final Report, Boeing Vertol Corp. Philadelphia, PA, March 1987

[18] Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. IEEE Transactions on Systems, Man and Cybernetics-Part A: Systems and Humans, 30: 286–297.

[19] Meyer, G. and Cicolani, L. S.A Formal Structure for Advanced Automatic Flight Control Systems. NASA Technical Note, NASA-TN-D-7940, May 1, 1975.

[20] Nicholas, O.P., and Bennett, P.J., "Proposed Wide Envelope Unified Control Concept for Vectored Thrust VSTOL Aircraft," Technical Memorandum FS312, Royal Aircraft Establishment RAE, Mar. 1980.

[21] Denham, J., and Paines, J., "Converging on a Precision Hover Control Strategy for the F-35B STOVL Aircraft," AIAA Guidance, Navigation and Control Conference and Exhibit, American Institute of Aeronautics and Astronautics, 2008. doi:10.2514/6.2008-6331.

[22] Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018 Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, 2018. doi:10.2514/6.2018-3847.

[23] Malpica, C., and Withrow-Maser, S., Handling Qualities Analysis of Blade Pitch and Rotor Speed Controlled eVTOL Quadrotor Concepts for Urban Air Mobility, Presented at the VFS International Powered Lift Conference 2020, San Jose, CA, January 21–23, 2020.

[24] Lombaerts, T., Kaneshige, J., Schuet, S., Hardy, G., Aponso, B. L., and Shish, K. H., "Nonlinear Dynamic Inversion Based Attitude Control for a hovering quad tiltrotor eVTOL vehicle," AIAA Scitech 2019 Forum, American Institute of Aeronautics and Astronautics, 2020. doi:10.2514/6.2019-0134.

[25] von Grünhagen, W., Schönenberg, T., Lantzsch, R. et al. Handling qualities studies into the interaction between active sidestick parameters and helicopter response types. CEAS Aeronaut J 5, 13–28 (2014). https://doi.org/10.1007/s13272-013-0079-7

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

[27] Anon., Heliport Design, AC150/5390-2C, Department of Transportation, Federal Aviation Administration, May 24, 2012.

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

[29] Decker, W. A., "Handling Qualities Evaluation of XV-15 Noise Abatement Landing Approaches Using a Flight Simulator," American Helicopter Society 57th Annual Forum, Washington D.C., 2001. URL https://rotorcraft.arc.nasa.gov/Publications/files/Decker.1CTR-8AHSPaper[1].pdf.

[30] FAA, Airworthiness Standards: Transport Category Rotorcraft, US Code of Federal Regulations 14 CFR 29, (https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-29) [retrieved 27 April 2023]

[31] FAA, Airworthiness Standards: Normal Category Airplanes, US Code of Federal Regulations 14 CFR 23, (https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-23)

[32] McRuer, D. T. "Interdisciplinary interactions and dynamic system integration," Int. J. of Control, vol. 59, no. 1, pp. 3–12, 1994.

[33] Hamel, P. G., "Rotorcraft-pilot coupling: A critical issue for highly augmented helicopters?" in AGARD Flight Vehicle Integration Panel Symposium on 'Advances in Rotorcraft Technology', Ottawa, Canada, May 1996, pp. 21–1–21–9.