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Flight Simulation-Driven Research into Simplified Vehicle Operations for Urban Air Mobility

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Final report

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16. Abstract

The goal of this project was to study the Simplified Vehicle Operations (SVO) paradigm for vertical takeoff and landing (VTOL) urban air mobility (UAM) aircraft through piloted simulations in two fixed-base flight simulators located at the Vehicle Systems, Dynamics, and Design Laboratory (VSDDL), part of the Department of Aerospace Engineering at Auburn University. A lift-plus-cruise (LPC) aircraft flight simulation model was deployed to two flight simulators, with identical cockpit display elements and core flight control system (FCS) architecture, which was based on the Total Energy Control System (TECS). The simulator setups differed in the design of the pilot inceptors and in the inceptor-to-command mappings. A total of twenty-one participants were recruited and classified into three groups depending on their flight experience or lack thereof. They included Certified Flight Instructors (CFI), individuals who held pilot's licenses and/or were undergoing pilot training, and individuals who held driver's licenses but did not have any piloting experience or training. Each participant flew the same tasks in both simulators, which included vertical reposition and hold, hovering turn and hold, lateral reposition and hold, pirouette, and precision hover handling qualities task elements (HQTE). A representative UAM mission that comprised takeoff and transition with obstacle clearance, en-route navigation, and landing approach with obstacle clearance was also simulated. In addition to data logged from the simulators, pilot experience summaries and feedback regarding the workload experienced during each simulated task were collected.

The piloted simulation campaign showed that participants, including the non-pilot individuals, were able to successfully fly the simulated tasks. Analysis of the simulator data, corroborated by participant feedback, revealed that coupling between inceptor axes occurred on both simulators, albeit in different manners and on different tasks for each. Analysis of the task workload debrief forms allowed calculation of Cooper-Harper handling qualities ratings for each participant, each task, and each simulator.

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Acronyms

AC	Airplane-centric
AOA	Angle of attack
CFI	Certified Flight Instructor
CHR	Cooper-Harper rating
CLC	Control loading computer
CMEL	Commercial Pilot License, Multi-Engine Land
CSEL	Commercial Pilot License, Single-Engine Land
DCC	Displays and controls computer
DVE	Degraded visual environment
FAA	Federal Aviation Administration
FCS	Flight control systems
FFM	Forward flight mode
FPA	Flightpath angle
HC	Helicopter-centric
HQTE	Handling qualities task element
IGC	Image generation computer
IR	Instrument rating
LHI	Left-hand inceptor
LNAV	Lateral navigation
LPC	Lift-plus-cruise
LQI	Linear quadratic integrator
MADCASP	Modular Aircraft Dynamics and Control Algorithm Simulation Platform
MSC	Master simulation computer
MTE	Mission task element
MTOM	Maximum takeoff mass
PEACE	Parametric Energy-based Aircraft Configuration Evaluator
PFD	Primary flight display
PIC	Pilot-in-command
PIO	Pilot-induced oscillation
PPL	Private Pilot License
RHI	Right-hand inceptor
RPC	Remote Pilot Certificate
RPM	Revolutions per minute
SPD	Speed
SPC	Student Pilot Certificate
SVO	Simplified Vehicle Operations
TECS	Total Energy Control System
UAM	Urban air mobility
VFM	Vertical flight mode
VNAV	Vertical navigation

VSDDL	Vehicle Systems, Dynamics, and Design Laboratory
VTOL	Vertical takeoff and landing

Executive Summary

The goal of this project was to investigate the Simplified Vehicle Operations (SVO) paradigm for vertical takeoff and landing (VTOL) urban air mobility (UAM) aircraft through piloted simulations in two fixed-base flight simulators at the Vehicle Systems, Dynamics, and Design Laboratory (VSDDL), part of the Department of Aerospace Engineering at Auburn University.

The same lift-plus-cruise (LPC) aircraft model was used in both simulators. The simulator setups differed in the physical design of the left-hand and right-hand inceptors and the inceptor-to-command mappings (i.e., response types, that were employed in their fly-by-wire flight control systems (FCS)). The downstream control system architecture, which was based on the Total Energy Control System (TECS) algorithm, was common to both setups. Additionally, both simulators had identical cockpit display setups.

A total of twenty-one participants were recruited and classified into three groups depending on their flight experience or lack thereof. Group A comprised five Certified Flight Instructors (CFIs), Group B comprised nine individuals who held pilot's licenses and/or were undergoing pilot training, and Group C comprised seven individuals who held driver's licenses but did not have any piloting experience or training. The study participants were given access to brief training videos describing in general terms how to fly each simulator setup. Each participant flew the same tasks in both simulators, which included vertical reposition and hold, hovering turn and hold, lateral reposition and hold, pirouette, and precision hover handling qualities task elements (HQTEs). A representative UAM mission that comprised takeoff and transition with obstacle clearance, en-route navigation, and landing approach with obstacle clearance was also simulated. In addition to data logged from the simulators, pilot experience summaries and feedback regarding the workload experienced during each simulated task were collected.

The piloted simulation campaign showed that participants, including the non-pilot individuals, were able to successfully fly the simulated tasks. Analysis of the task workload debrief forms allowed the calculation of Cooper-Harper handling qualities ratings for each participant, for each task, on each simulator. Analysis of the simulator data, corroborated by participant feedback, revealed that coupling between inceptor axes occurred on both simulators, albeit in different manners and on different tasks for each. A usability analysis of the inceptors and refinement of their design is proposed for subsequent work. Certain deficiencies in the behavior of the position hold control system and the flight director were identified and will be rectified for future work. Logical avenues for future work include simulation of wind, gust, and turbulence, flight in degraded visual environment (DVE), additional forward flight HQTEs, and simulation of off-nominal scenarios with degraded handling qualities or system failures.

1 Introduction

The recent spate of novel vertical takeoff and landing (VTOL) or short takeoff and landing (STOL) aircraft design efforts (including, but not limited to (Joby Aviation, n.d.; Beta Team, n.d.; Wisk Aero, n.d.; Archer Aviation, n.d.; Electra Aero, n.d.) (Volocopter, 2018; Lilium, 2018; Aurora Flight Sciences, 2018)) aimed at on-demand mobility (ODM) and urban air mobility (UAM) operations (Uber Elevate, 2018; FAA, 2020; Garrow, German, & Leonard, 2021; Goodrich & Theodore, 2021; Kohlman, Patterson, & Raabe, 2019) and featuring all-electric propulsion systems with distributed propulsors is notable.

The Simplified Vehicle Operations (SVO) paradigm for UAM flight vehicles aims to ensure that pilots can operate them safely and proficiently with substantially reduced pilot workload and training requirements. Whereas technology infusion into flight decks has historically necessitated additional pilot training and currency requirements, the SVO approach is to infuse technologies into the aircraft that dramatically reduce pilot workload, build in protection, and reduce training requirements (GAMA, 2019; GAMA, 2020). Therefore, it requires a holistic and integrated approach to the design of: (i) inceptors, (ii) flight control laws, and (iii) cockpit displays. This work, funded by the Federal Aviation Administration (FAA), analyzes some aspects of the above through piloted flight simulations of a lift-plus-cruise (LPC) electric VTOL (e-VTOL) aircraft model using two fixed-base flight simulators developed at the Vehicle Systems, Dynamics, and Design Laboratory (VSDDL), part of the Department of Aerospace Engineering at Auburn University.

With regard to inceptors, as UAM designs combine characteristics of both conventional fixed-wing aircraft and rotorcraft, there is legitimate debate regarding whether, or to what extent the cockpit control inceptors should resemble those found in conventional fixed-wing aircraft or rotorcraft. In addition to their ergonomic design, the mapping between the inceptor axes and the motion variables commanded by pilot inputs along those axes will likely impact pilot performance and must therefore be studied (see, for example, (Lombaerts, Kaneshige, & Feary, 2020; Dollinger, Reiss, Angelov, Loebl, & Holzapfel, 2021; Duerksen, 2003; Beringer, 2002; Beringer, 1999). In this work, two inceptor layouts were assessed. An *airplane-centric* (AC) inceptor layout was implemented in VSDDL Flight Simulator #1 (dubbed *Blue Sim*) and a *helicopter-centric* (HC) inceptor layout in VSDDL Flight Simulator #3 (dubbed *Red Sim*).

With regard to flight control laws, the novel configurations of UAM aircraft, their VTOL capability, their over-actuated designs (more control effectors than control degrees of freedom), and the requirement to transition between forward flight mode (FFM) and vertical flight mode

(VFM) present simultaneous opportunities and challenges for the design of advanced flight control systems (FCS). SVO goals necessitate FCS designs that guarantee stability and controllability while simultaneously allowing intuitive augmented manual control. While a multitude of FCS designs for fixed-wing aircraft and rotorcraft are reported in literature, the FCS architecture employed in this work for both AC and HC setups has the Total Energy Control System (TECS) at its core for the longitudinal dynamics. TECS, which was originally developed for fixed-wing applications and is based on total energy principles, provides decoupled speed and flightpath responses through coordinated control of thrust and pitch attitude; see Lambregts earlier work (Lambregts A. , 1983c; Lambregts A. , 1983a; Lambregts A. , 1983b; Lambregts A. , 1983d)) and more recent work (Lambregts, 2013; Lambregts, 2006).

TECS has been successfully flight-tested on multiple fixed-wing platforms (Lambregts, 2006; Bruce, Kelly, & Person, 1986; Bruce R. , 1987; Bruce R. , 1989; Faleiro & Lambregts, 1999) . Additional studies analyzing, extending, or improving TECS performance for fixed-wing applications are reported; see (Eladl, et al., 2008; Maclosky, Mathisen, & Leiphon, 2012; Ganguli & Balas, 2001; Chudy & Rzucidlo, 2009a; Chudy & Rzucidlo, 2009b) (Chudy & Rzucidlo, 2011a; Chudy & Rzucidlo, 2011b; Chakraborty, Lozano, & Mavris, 2015; Cooper, 2014; Voth & Ly, 1991) (Kaminer & O'Saughnessy, 1991; Lamp & Luckner, 2013; Weibel & Lawrence, 2013; Niedermeier & Lambregts, 2009; Degaspare & Kienitz, 2020).

More recent works (Chen, Chen, Yang, & Jeng, 2007; Vasquez-Beltran & Rodriguez-Cortes, 2015; Hernandez-Garcia & Rodriguez-Cortes, 2013; Chen, Zhang, Zhang, & Shen, 2017; Zhang, Zhiming, Wang, & Wu, 2019) (Deng, Wu, & You, 2021; Jimenez, Lichota, Agudelo, & Rogowski, 2020; Chakraborty, Ahuja, Comer, & Mulekar, 2019; Chakraborty I. , Mishra, Comer, & Leonard, 2021; Comer & Chakraborty, 2023) describe the use of TECS for VTOL configurations, including helicopters, quad-rotors, tilt-rotors, and LPC.

Regarding cockpit displays, the major challenge is to design them to provide the necessary information to the pilot without causing information overload. In SVO architectures where the pilot commands a higher-level trajectory variable (e.g., flightpath angle) as opposed to an attitude variable (e.g., pitch attitude), it may be possible to simplify the instrument information presented to the pilot (Duerksen, 2003). A modified primary flight display (PFD) was developed for this purpose.

Given the unique nature of UAM aircraft, it is desirable to provide, in addition to information regarding flight states and systems, information regarding expended control effort (an awareness of impending control saturation) and current FCS operating mode (a defense against mode confusion). Indications for these factors were also incorporated into the cockpit displays. The cockpit display elements and layout were standardized between AC and HC setups.

The FAA has proposed to adapt military methodologies called mission task elements (MTEs) that are outlined in ADS-33E-PRF (United States Army, 2000) after modifying them suitably for VTOL aircraft performing civilian missions under civil certification rules (Mitchell, Klyde, Shubert, Sizoo, & Schaller, 2022; Klyde, et al., 2020; Klyde, Lampton, Mitchell, Berka, & Rhinehart, 2021) . Handling qualities MTEs or handling qualities task elements (HQTEs) are part of a mission-oriented approach in which they are intended to represent realistic maneuvering elements of the mission.

The HQTEs that were the basis for the piloting tasks considered in this work included:

- vertical reposition and hold,
- hovering turn and hold,
- lateral reposition and hold,
- pirouette,
- precision hover, and
- UAM heliport approach.

These tasks were carried out by participants who were classified into three groups: Group A - aviators holding instructor certificates, Group B - licensed pilots and students undergoing flight training at any level, and Group C - individuals holding driver's licenses but no pilot's license and with no prior piloting experience or training.

2 Flight simulator setup

2.1 Flight simulator #1 / Blue Sim – airplane-centric (AC) setup

Flight simulator #1, dubbed as *Blue Sim* for the project, is shown in Figure 1. It has a reconfigurable cockpit in terms of seating arrangements (centerline, side-by-side, or tandem), and width (between 30” and 72”) and height (between 34” and 54”). Centerline seating configuration was chosen for this work, with a cockpit width of 40” and height of 44”. External views are shown on five displays, with forward view displayed on a single 75” wide by 42.2” high, 3840 × 2160 resolution screen, and side views displayed using four 29.6” wide by 16.7” high, 2560 × 1440 resolution screens. Two of the side screens are positioned directly to the left and right of the pilot while the remaining two are positioned directly to the left and right of the back seat occupants. The cockpit displays include three touchscreens: a 13.4" wide by 10.7" high 1920 × 1080 resolution center display, with a 21.3" wide by 12.3" high 1920 × 1080 resolution display on either side. Additionally, there is an iPad Mini-based moving map display (that uses the Garmin Pilot™ application) and a 6.1" wide by 3.4" high 1080 × 1920 resolution screen used to display a downward-looking view.

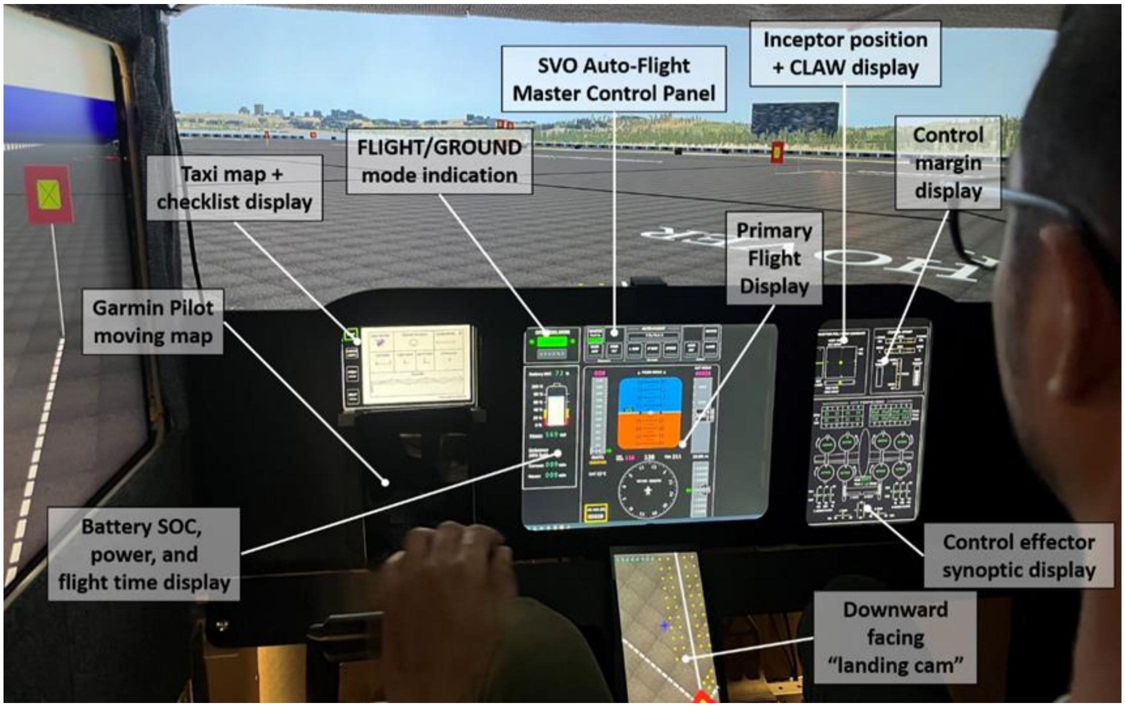

Figure 1. Flight simulator #1 (Blue Sim) used for airplane-centric (AC) setup

2.2 Flight simulator #3 / Red Sim – helicopter-centric (HC) setup

Flight Simulator #3, dubbed *Red Sim* for this project, is shown in Figure 2. It is based on a Diamond DA40 cabin. While the simulator has side-by-side seating arrangements for both the front and aft row of seats, centerline seating was set up in the front row for this project. Five 1080p overhead projectors are used to project external visuals onto a 16 ft diameter 270° horizontal field-of-view cylindrical screen with 90" image height. The images cast from the projectors are blended and corrected for distortion (due to projection onto a cylindrical surface) using Pixelwix warp-and-blend software. The main cockpit displays include three touchscreens, a 13.4" wide by 10.7" high 1920 × 1080 resolution center display, with a 6.5" wide by 11.6" high 1080 × 1920 resolution display on either side. An iPad Mini-based moving map display (that uses the Garmin Pilot™ application), and a 6.1" wide by 3.4" high 1080 × 1920 resolution screen display (to show a downward-looking view) are used in addition to the main cockpit displays.

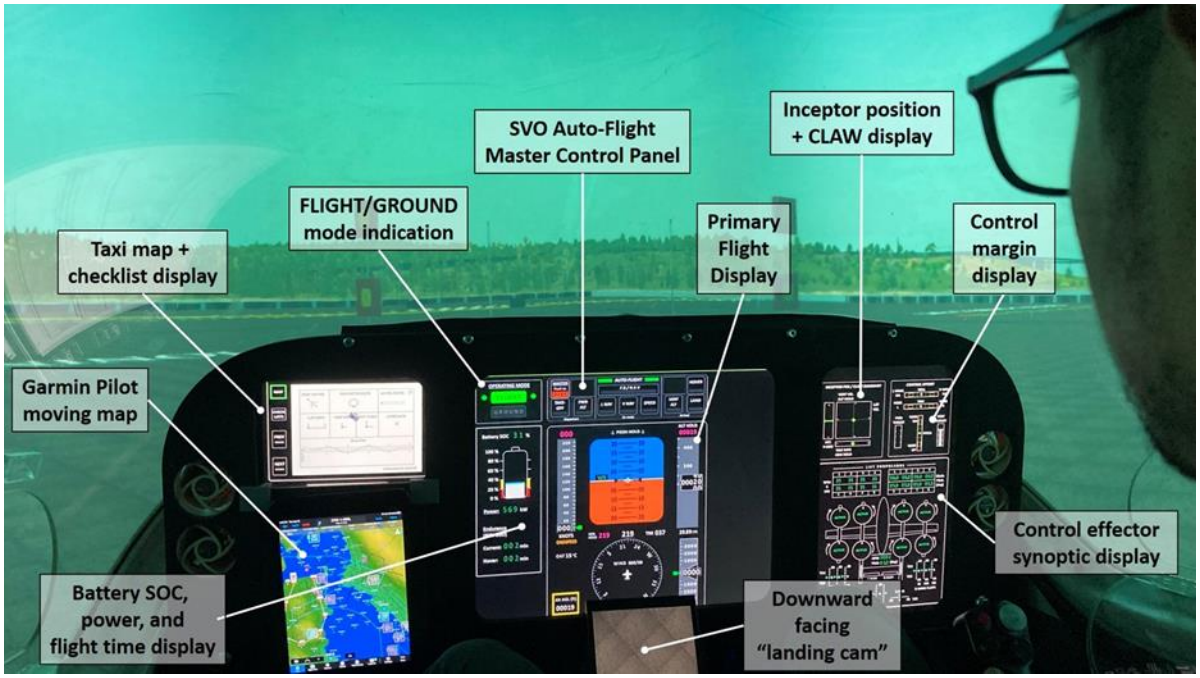

Figure 2. Flight Simulator #3 (Red Sim) used for helicopter-centric (HC) setup

2.3 Common systems architecture

The common systems architecture for both simulators, which comprise multiple computers that are networked together, is shown in Figure 3. The master simulation computer (MSC) runs the flight simulation model and computes the aircraft trajectory during flight. The trajectory is transmitted to the image generation computers (IGCs), of which there are three in Blue Sim and two in Red Sim. They render the external (out-the-window) views using X-Plane, which is used only for generating external visuals and querying terrain elevation but not for any computational function. The displays and controls computer (DCC) receives aircraft trajectory, system states, and control effector states from the MSC and uses them to drive the cockpit displays and generate audio. The DCC is also used to communicate the pilot's interaction with the FCS through the inceptors or the touchscreen displays to the MSC. The control loading computer (CLC), which is meant to drive control loading actuators that provide force feedback for the cockpit controls, is not present in either Blue Sim or Red Sim.

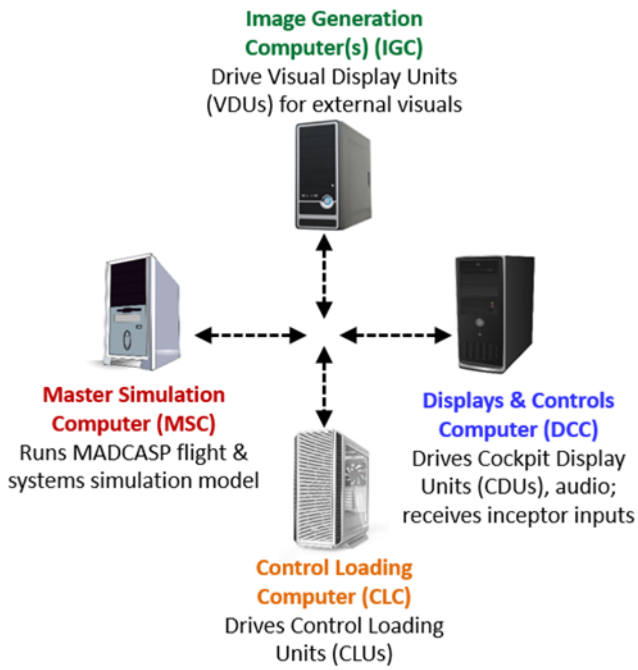

Figure 3. Simulator computers and communication architecture

2.4 Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP)

The *Modular Aircraft Dynamics and Control Algorithm Simulation Platform* (MADCASP) is a MATLAB/Simulink-based stability and control assessment and flight simulation platform that has been developed by VSDDL with funding from NASA Langley Research Center under the Transformational Tools and Technologies (TTT) project (NASA, 2018). The top-level layout of the Simulink model which lies at the core of the MADCASP is shown in Figure 4. The FCS architectures are incorporated inside the *Flight Controls* block. Control effector commands are generated as the output from this block. The aero-propulsive and key systems models (e.g., power, energy, and actuation) are incorporated in the *Flight Mechanics & Systems Models* block. The net forces and moments and the angular momenta of spinning/rotating subsystems are computed inside this block. The *Vehicle Equations of Motion Integration* block computes the vehicle motion using six-degree-of-freedom rigid body equations of motion. These equations of motion are written in body-fixed axes with respect to a fixed vehicle reference point, which may be offset from the center of gravity. The position of the vehicle during flight is described by the current latitude, longitude, and geocentric radius. Quaternions are used as attitude descriptors in the equations of motion. The flat-earth position and the 3-2-1 Euler angle sequence are post-processed from the primary position and attitude descriptors. The *Mass Properties* block tracks the change in vehicle mass-properties due to configuration changes. The *Communication Interface* block is used to interface MADCASP with flight simulators for piloted simulations, where MADCASP executes on the MSC and exchanges data with the other simulator computers (IGC, DCC, CLC). In addition to real-time simulation, the MADCASP framework is also used for pre-processing tasks which include generalized trim analysis (in which trim is solved as a constrained optimization problem), model linearization, and dynamic stability analysis.

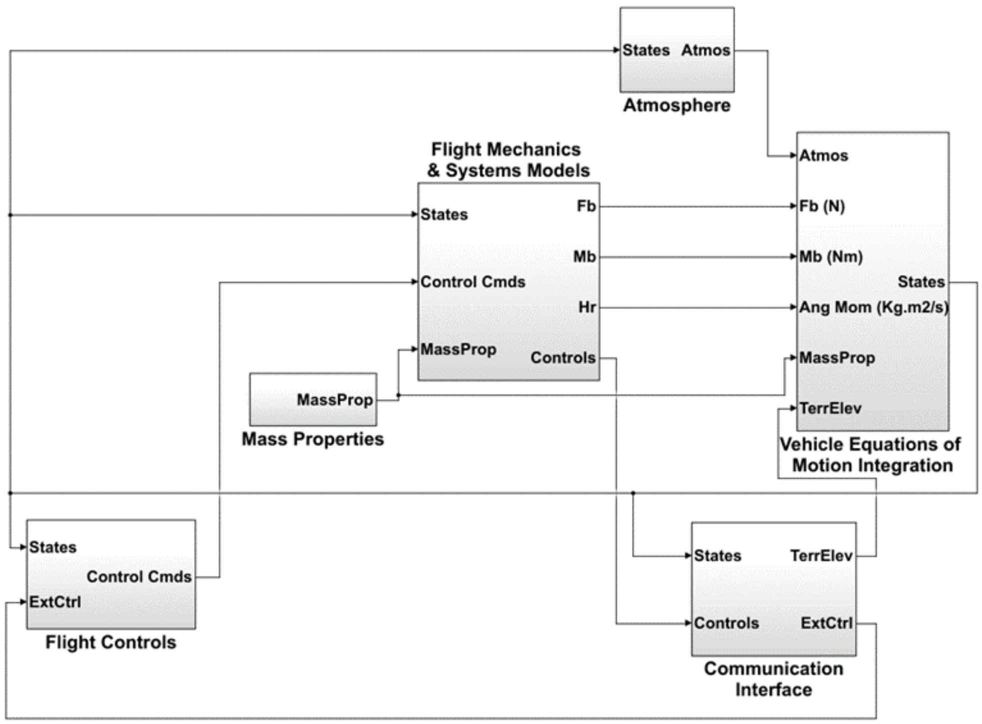

Figure 4. Top-level of MADCASP Simulink model

3 Simplified Vehicle Operations (SVO) setup

3.1 Flight control laws

3.1.1 Flight control system architecture

The LPC-03 configuration is shown in Figure 5. It has a total of eight identical lift propulsors and one pusher cruise propulsor, which are each driven by an electric motor and are of a constant-speed propeller design.

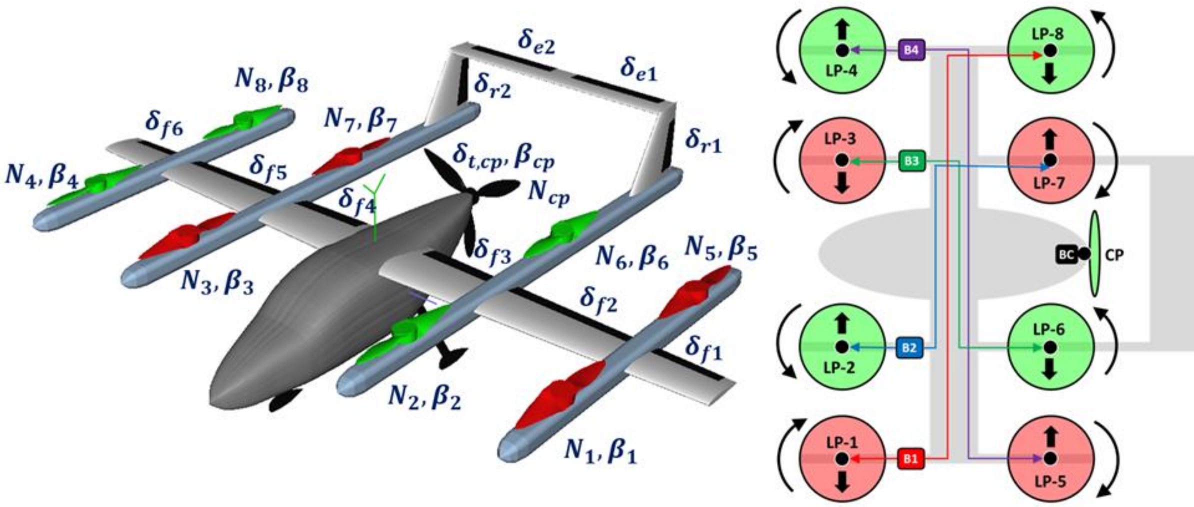

Figure 5. LPC-03 configuration overview

The lift propulsors are mounted on inboard and outboard booms which are fixed to the wings, with two lift propulsors per boom. Each wing has an inboard flaperon (inboard of the inboard boom), a midboard flaperon (between the two booms), and an outboard flaperon (outboard of the outboard boom). Twin vertical stabilizers, each containing a rudder, are mounted at the aft ends of the inboard booms. A single horizontal stabilizer, containing two elevators, is mounted on top of the vertical stabilizers. The flaperons, elevators, and rudders are used to control roll, pitch, and yaw respectively in FFM. In VFM, roll is controlled using differential thrust between left-side and right-side lift propulsors. Pitch is controlled through differential thrust between fore and aft lift propulsors. The lift propulsor axes are canted inboard or outboard, as shown in Figure 5, to generate yawing moments from the lateral thrust components. For each lift propulsor, the yawing moment so generated is in the same direction as its aerodynamic reaction torque. Yaw is controlled by increasing thrust on all lift propulsors that create a yawing moment in the desired direction while reducing thrust on the remaining. The configuration was sized for a representative UAM mission (Figure A-1) using the Parametric Energy-based Aircraft Configuration Evaluator (PEACE) sizing framework. Further details regarding PEACE and its use to size the LPC-03 concept are provided in other work by Chakraborty & Mishra (2022; 2020). The characteristics of the sized aircraft are summarized in Appendix A, Table A- 1, and are used as the starting point for FCS development. An overview of the FCS architecture from the inceptors to the vehicle control effectors is shown in Figure 6. The full list of control effectors is given in Table 1. The AC and HC setups differ in the physical design of the inceptors as well as the inceptor-to-command mappings that are employed. The rest of the FCS architecture is identical between the AC and HC setups, as indicated in Figure 6 by the shaded locks.

Table 1. LPC-03 control effectors

#	Symbol	Description	Unit
1-3	$\delta_{f1}, \delta_{f2}, \delta_{f3}$	Flaperon, left wing, out-/mid-/inboard	deg
4-6	$\delta_{f4}, \delta_{f5}, \delta_{f6}$	Flaperon, right wing, in-/mid-/outboard	deg
7, 8	δ_{e1}, δ_{e2}	Left, right elevator	deg
9, 10	δ_{r1}, δ_{r2}	Left, right rudder	deg
11	$\delta_{t,cp}$	Cruise prop throttle setting	--
12	β_{cp}	Cruise prop blade pitch	deg
13	N_{cp}	Cruise prop revolutions per minute (RPM)	RPM
14-21	N_{1-8}	Lift prop RPMs	RPM
22-29	β_{1-8}	Lift prop pitches	deg

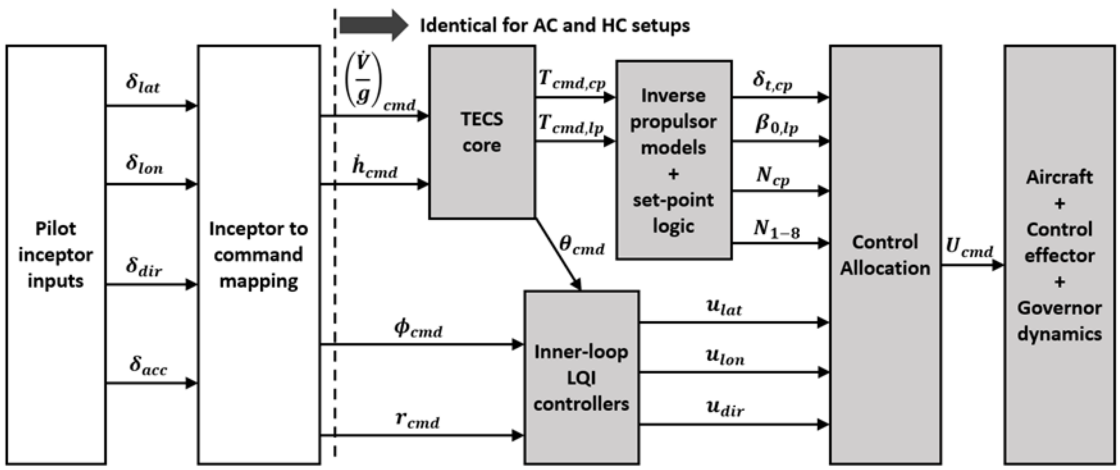

Figure 6. Inceptor-to-effector FCS architecture for LPC-03

3.1.2 Holds

The holds include heading hold, track hold, altitude hold, and position hold. The implementation is identical for both Blue Sim and Red Sim. The modes engage and disengage automatically based on the state of the aircraft and inputs received from the inceptors. The pilot does not directly engage any of these holds but can disengage them through inceptor inputs.

3.1.3 Heading and track hold

Heading hold is engaged below 40 knots if directional input δ_{dir} = 0 and yaw rate is below a threshold. Track hold is engaged above 70 knots if lateral input δ_{lat} = 0 and bank angle is below a threshold. Based on the error between actual and target heading or track, a turn rate command (for heading hold) or a bank command (for track hold) is generated by PI control action.

3.1.4 Altitude hold

The altitude hold in VFM and FFM is identical and is engaged when the longitudinal pilot input δ_{lon} is below a specified threshold and the climb rate is below a specified threshold. The reference altitude established at engagement is maintained with the PI control logic.

3.1.5 Position hold

This is only engaged in hover conditions when the total airspeed (forward and lateral) is below a specified threshold and $\delta_{lat}, \delta_{lon}$, and δ_{acc} inceptors are centered. Longitudinal and lateral positioning errors are calculated relative to an *anchor point* that is established at engagement, and used to generate an acceleration command for the longitudinal axis and a bank angle command for the lateral axis using proportional-integral-derivative (PID) control action.

3.1.6 Downstream FCS architecture

The downstream FCS architecture (see Figure 6) is common to both AC and HC setups. For both setups, the inceptor-to-command mappings generate the following commands: (i) normalized acceleration command $(\dot{V}/g)_{cmd}$, (ii) altitude rate command $\dot{h}_{cmd}$, (iii) bank angle command ϕ_{cmd}, and (iv) yaw rate command r_{cmd}. Moving left-to-right across Figure 6, the remaining FCS modules comprise the following:

- **TECS core algorithm (Section 3.1.7):**

  Using the normalized acceleration $(\dot{V}/g)_{cmd}$ and height rate $\dot{h}_{cmd}$ commands, the modified TECS algorithm generates a thrust command $T_{cmd,lp}$ for the lift propulsors, a thrust command $T_{cmd,cp}$ for the cruise propulsor, and a pitch attitude command θ_{cmd}.

- **Inner-loop LQI controllers (Section 3.1.8):**

  Based on the commanded pitch angle θ_{cmd}, bank angle ϕ_{cmd}, and yaw rate r_{cmd}, the inner-loop controllers use linear quadratic integral (LQI) logic to generate normalized variables u_{lat}, u_{lon}, and $u_{dir} \in [-1, +1]$ that denote control effort about lateral (roll), longitudinal (pitch), and directional (yaw) axes.

- **Inverse propulsor models and set-point logic:**

  The cruise propulsor inverse model calculates the cruise propulsor throttle setting $\delta_{t,cp}$ based on the cruise propulsor thrust command $T_{cmd,cp}$ and the flight condition. The lift propulsor inverse model calculates $\beta_{0,lp}$, a common blade pitch component shared by all lift propellers, based on the lift propulsor thrust command $T_{cmd,lp}$ and the flight condition. The set-point logic for lift propellers varies their revolutions per minute (RPM) to maintain $\beta_{0,lp}$ at a defined set-point.

- **Control allocation (Section 3.1.9):**

  The control allocation and set-point logic then map the control groups to the 29 control effector states listed in Table 1.

3.1.7 Modified TECS controller architecture

The classical TECS algorithm uses flightpath angle (FPA) γ and utilizes small angle assumptions. For low-speed flight in VFM, the FPA may be large enough to invalidate the small angle assumption. Further, for a vertical climb or descent, all vertical velocities map to γ = 90° or γ = −90°, limiting the use of FPA as a feedback parameter entirely. Therefore, the classical implementation is modified by using $\dot{h}$ in place of γ. To do so, a quantity F is defined as follows:

$$F = \min\left(1, \frac{1}{|V|}\right) \quad 1$$

The product quantities $F\dot{h}_{cmd}$ and $F\dot{h}$ are used in place of the classical γ_{cmd} and γ. Per the equation above, at higher speeds, $F = 1/V$, and noting that $\dot{h} = V \sin\gamma$, it follows that $F\dot{h}_{cmd} = \dot{h}_{cmd}/V = \sin\gamma_{cmd} \approx \gamma_{cmd}$ and also $F\dot{h} = \dot{h}/V = \sin\gamma \approx \gamma$. Thus, in this scenario, the modified TECS logic effectively operates on FPA, similar to the classical scheme (Lambregts, 2013). However, for low speeds and hovering flight, F = 1, and therefore, $F\dot{h}_{cmd} = \dot{h}_{cmd}$, $F\dot{h} = \dot{h}$. In this scenario, the modified TECS operates on vertical velocity directly.

The classical TECS scheme generates two outputs: a thrust command and a pitch attitude command. For the case of the LPC configuration, however, there are two propulsor types (cruise propulsor and lift propulsors) that generate thrust in orthogonal directions. As a result, the modified TECS scheme for the LPC configuration has three outputs: cruise propulsor thrust command $T_{cmd,cp}$, lift propulsor thrust command $T_{cmd,lp}$, and pitch attitude command θ_{cmd}. The generation of these commands is shown in block diagram form in Figure 7 and Figure 8. The specific total energy rate and error are computed separately for the cruise propulsor ($\dot{E}_{cp}$ and $\dot{E}_{e,cp}$) and lift propulsors ($\dot{E}_{lp}$ and $\dot{E}_{e,lp}$). The modified TECS control action is then given by:

$$T_{cmd,cp} = W\left(\frac{K_{I,cp}}{s}\dot{E}_{e,cp} - K_{P,cp}\dot{E}_{cp}\right) \quad 2$$

$$T_{cmd,lp} = W\left(\frac{K_{I,lp}}{s}\dot{E}_{e,lp} - K_{P,lp}\dot{E}_{lp}\right) \quad 3$$

$$\theta_{cmd} = -\left(\frac{K_{I,\theta}}{s}\dot{L}_e - K_{P,\theta}\dot{L} + K_{\dot{V}\to\theta}^{FF}\frac{\dot{V}}{g}_{cmd} - K_P^{FF}\ddot{h}_{cmd}\right) \quad 4$$

As seen in Figure 7 and Figure 8, the acceleration and vertical velocity signal paths are modified by a set of modifier variables $\zeta_{x\to y}$ (controlling whether signal ‘x’ propagates forward and affects the computation for ‘y’), namely:

- acceleration to cruise propulsor, $\zeta_{\dot{V}\to cp}$
- vertical velocity to cruise propulsor, $\zeta_{\dot{h}\to cp}$
- acceleration to lift propulsor, $\zeta_{\dot{V}\to lp}$
- vertical velocity to lift propulsor, $\zeta_{\dot{h}\to lp}$
- acceleration to pitch, $\zeta_{\dot{V}\to\theta}$
- vertical velocity to pitch, $\zeta_{\dot{h}\to\theta}$
- vertical velocity to pitch (proportional path), $\zeta_{\dot{h}\to\theta,P}$

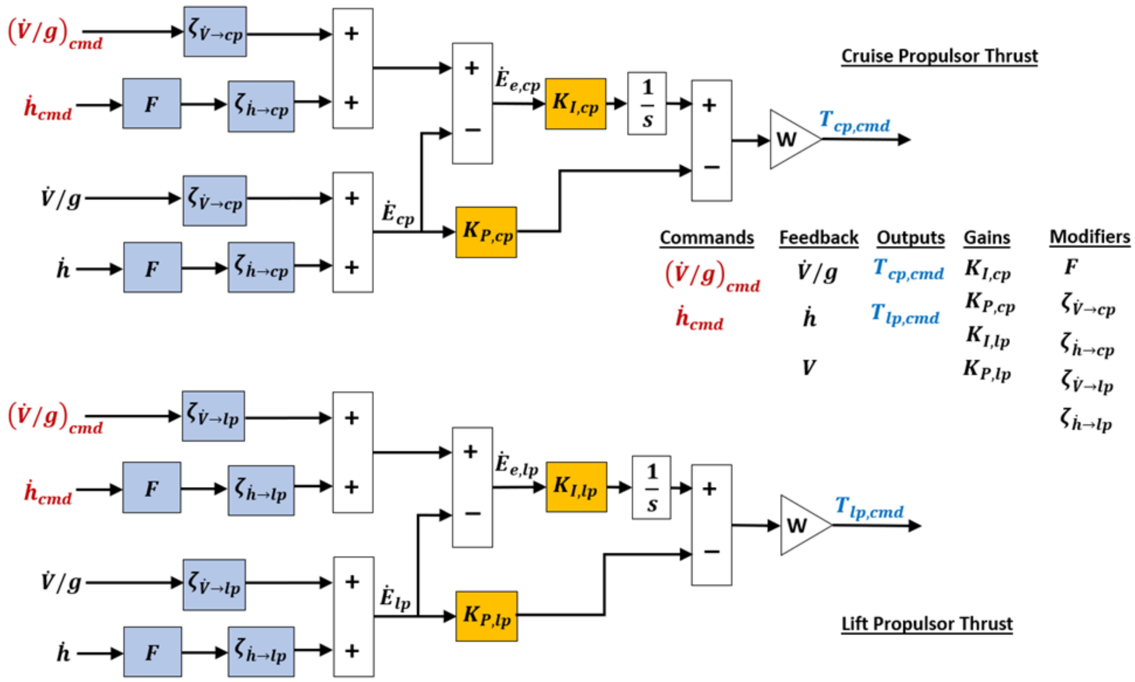

Figure 7. Modified TECS control system architecture cruise and lift propulsor channels

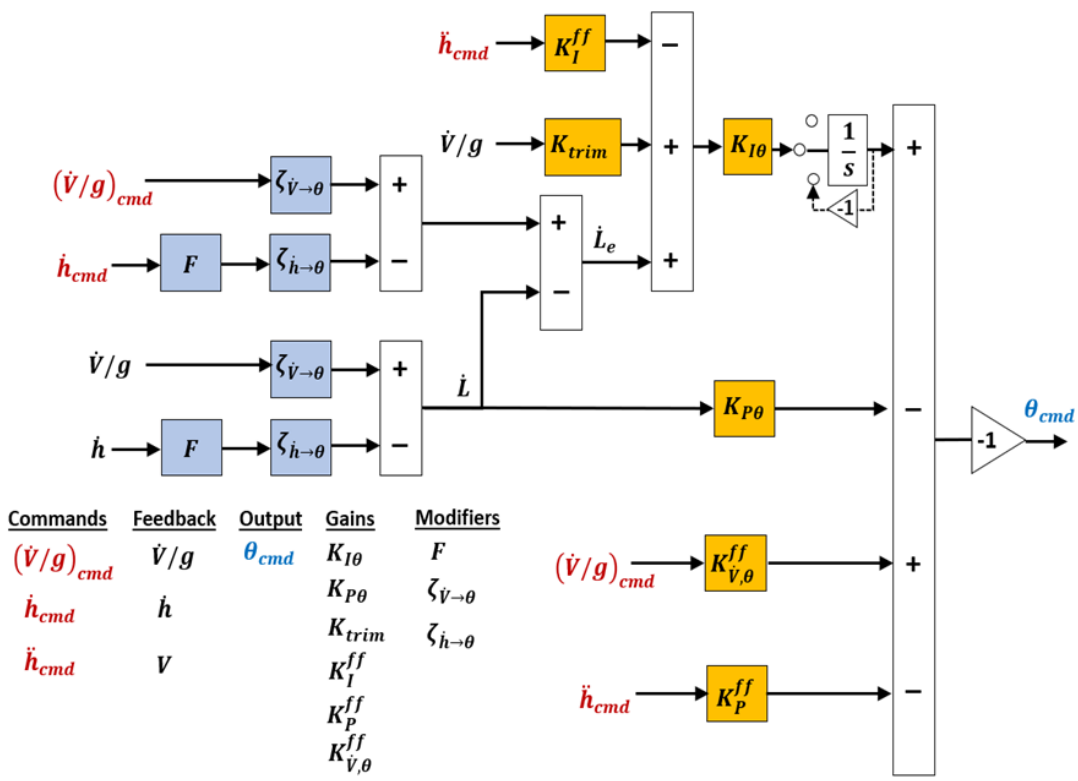

Figure 8. Modified TECS control system architecture pitch channel

The variation of these parameters are best explained by considering VFM, transitioning flight, and FFM scenarios separately, as follows:

- **Vertical flight:**

  In VFM, the cruise propulsor is merely idling and does not respond to acceleration, vertical velocity commands, or feedback. Therefore, $\zeta_{\dot{V}\to cp} = \zeta_{\dot{h}\to cp} = 0$. Vertical velocity commands $\dot{h}_{cmd}$ are achieved using the thrust of the lift propulsors while maintaining a level pitch attitude. Therefore, $\zeta_{\dot{h}\to lp} = 1$, but $\zeta_{\dot{V}\to\theta} = 0$. Forward acceleration/deceleration commands $(\dot{V}/g)_{cmd}$ are realized by changing the pitch attitude of the aircraft to tilt the lift propulsor net thrust vector and adjusting the lift propulsor thrust. Therefore $\zeta_{\dot{V}\to lp} = \zeta_{\dot{V}\to\theta} = 0$.

- **Transitioning flight:**

  In transition flight, the cruise propulsor responds to acceleration commands, thus $\zeta_{\dot{V}\to cp} = 1$. However, it does not respond to vertical velocity commands, thus $\zeta_{\dot{h}\to cp} = 0$. The lift propulsors continue to respond to vertical velocity commands, but no longer respond to acceleration commands. Therefore, $\zeta_{\dot{h}\to lp} = 1$, but $\zeta_{\dot{V}\to lp} = 0$. A level deck (pitch attitude) is maintained, and neither acceleration nor vertical velocity commands or feedback cause changes in pitch attitude. Therefore, $\zeta_{\dot{V}\to\theta} = \zeta_{\dot{h}\to\theta} = 0$. The level deck is maintained by discharging the integrator state in the pitch channel. This logic is shown in Figure 8.

- **Forward flight:**

  In FFM, the lift propulsors are inactive. Therefore, by default, $\zeta_{\dot{h}\to lp} = \zeta_{\dot{V}\to lp} = 0$. FFM operation can be divided into three scenarios depending on whether the cruise propulsor throttle setting $\delta_{t,cp}$ is unsaturated ($0 < \delta_{t,cp} < 1$) or saturated ($\delta_{t,cp} = 0{,}1$). If unsaturated, acceleration and flightpath commands can be tracked simultaneously. However, if saturated, it is necessary to prioritize tracking of either flightpath (path priority) or speed (speed priority). These scenarios are as follows:

  - **Throttle unsaturated:**

    Similar to the classical TECS scheme, the cruise propulsor now controls the specific total energy rate by responding to both acceleration and vertical velocity commands (and feedback), thus $\zeta_{\dot{V}\to cp} = \zeta_{\dot{h}\to cp} = 1$. Vertical velocity commands and feedback result in the development of pitch attitude commands, therefore $\zeta_{\dot{h}\to\theta} = 1$ and $\zeta_{\dot{h}\to\theta,P} = 1$. However, acceleration commands do not directly result in pitch attitude commands, therefore $\zeta_{\dot{V}\to\theta} = 0$. This last setting, $\zeta_{\dot{V}\to\theta} = 0$, is consistent with the updated TECS scheme (Lambregts, 2013), where it was found to reduce the flightpath transient while accelerating or decelerating. The original TECS formulation corresponded to $\zeta_{\dot{V}\to\theta} = 1$. The removal of acceleration to pitch singal propagation is compensated with the gain K_{TRIM}, which is designed to re-trim the pitch attitude as airspeed changes, providing progressive nose-down pitch as the aircraft accelerates.

- **Throttle saturated, speed priority:**

  Speed is prioritized by linearly washing in $\zeta_{\dot{V}\to\theta} = 1$ while washing out $\zeta_{\dot{h}\to\theta} = 0$ and maintaining the proportional damping channel $\zeta_{\dot{h}\to\theta,P} = 1$. Acceleration commands and feedback then contribute to the computation of the pitch attitude command θ_{cmd}, while vertical velocity commands and feedback do not. However, the pitch-damping proportional channel remains active so as to not introduce a sudden pitch transient. The speed priority logic uses θ_{cmd} to track the commanded acceleration, while the resulting vertical velocity (flightpath) becomes an open-loop fallout from the specific energy rate balance. Speed priority is engaged if the throttle saturates in a speed range that requires *underspeed* or *overspeed* protection. For this aircraft, *underspeed* corresponds to an airspeed threshold below which wing-borne flight cannot be sustained without exceeding a threshold angle of attack (AOA) limit.

- **Throttle saturated, path priority:**

  When path is prioritized, there is no closed-loop control of speed, which becomes an open-loop fallout parameter. In this case, $\zeta_{\dot{V}\to\theta} = 0$, $\zeta_{\dot{h}\to\theta} = 1$, and $\zeta_{\dot{h}\to\theta,P} = 1$. The path priority logic uses θ_{cmd} to track the commanded flightpath, while the resulting acceleration/deceleration becomes a fallout from the specific energy rate balance. Path priority is engaged if throttle saturation occurs in a speed range where *underspeed* and *overspeed* are not imminent threats.

The variation of these modifiers over the velocity range of the aircraft is depicted in Figure 9. As shown in Figure 9, linear wash-in/wash-out logic is used to effect changes in the values of the $\zeta_{()}$ variables. These occur in the speed range of 40-45 knots (blend between vertical and transition flight modes) and between 135-140 knots (blend between transition and FFM).

The modified TECS algorithm incorporates a total of three feed-forward gains. The first two (K_I^{FF} and K_P^{FF}) were proposed by Niedermeier and Lambregts (Niedermeier & Lambregts, 2009) for increased aircraft response in forward flight. The third feed-forward gain was proposed for increasing aircraft responsiveness to acceleration commands during vertical flight mode. For hover or near-hover flight conditions with $\theta \approx 0$, the small angle approximation gives $\cos\theta \approx 1$ and $\sin\theta \approx \theta$. The force balance in the vertical direction yields $\sum T_{lp} \cos\theta = mg \rightarrow \sum T_{lp} = mg/\cos\theta \approx mg$, where $\sum T_{lp}$ is the net thrust of all lift propulsors combined. The equation of motion in the horizontal direction yields $\sum T_{lp} \sin -\theta = m\dot{V} \rightarrow -\theta \approx \sin(-\theta) = m\dot{V}/\sum T_{lp}$. Combining the two results yields $\theta \approx -m\dot{V}/(mg) = \dot{V}/g$. Writing this result in terms of command quantities yields $\theta_{cmd} = -\dot{V}_{cmd}/g = -K_{\dot{V}\rightarrow\theta}^{FF}(\dot{V}_{cmd}/g)$, with $K_{\dot{V}\rightarrow\theta}^{FF} = 1$. This establishes the feed-forward gain $K_{\dot{V}\rightarrow\theta}^{FF}$ that relates commanded acceleration $\dot{V}_{cmd}/g$ to commanded pitch attitude θ_{cmd} and has nominal value of 1 at hover. As speed increases, this gain is given a linear washout as:

$$K_{\dot{V}\rightarrow\theta}^{FF} = \max\left(0{,}1 - \frac{|V|}{40}\right) \qquad 5$$

The purpose of the gain K_{TRIM} is to bring about a change in pitch attitude appropriate for the change in speed without affecting flightpath. As the aircraft accelerates to higher speeds, there must be a simultaneous nose-down pitch rate (i.e., reduction in AOA) to maintain balance of forces in the direction normal to the flightpath. Referring to Figure 8, the pitch rate command generated by the K_{TRIM} channel is given by:

$$-\dot{\theta} = K_{TRIM} K_{I,\theta} \frac{\dot{V}}{g} \qquad 6$$

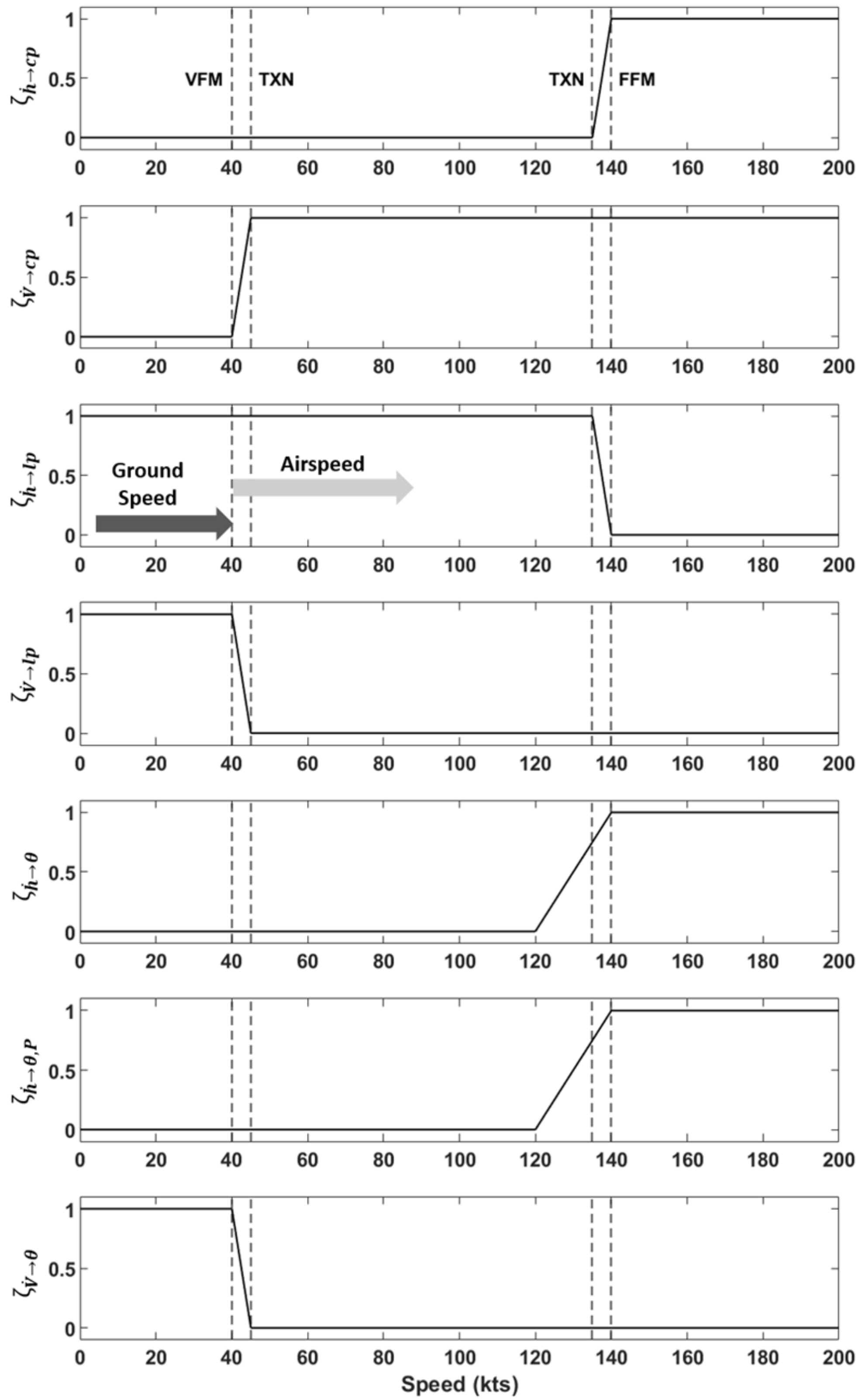

Figure 9. Modified TECS control system architecture modifier variables for normal flight condition

3.1.8 Inner-loop controller architecture

The inner-loop controller comprises a linear quadratic regulator with integral action (LQI) for longitudinal and lateral/directional control. The inner-loop control action is given by:

$$u_{lon} = -K_{lon}^{1x4}[w \quad q \quad \theta \quad \int e_\theta dt]^T \qquad 7$$

$$[u_{lat} \;\; u_{dir}]^T = -K_{lat}^{2x5}[p \quad r \quad \phi \quad \int e_\phi dt \quad \int e_r dt]^T \qquad 8$$

where e_θ, e_ϕ, and e_r are the tracking errors of the tracked variables (command minus fed back value) which are integrated over time (as part of the integral action).

3.1.9 Control allocation

The full list of control effectors for the LPC-03 is shown in Table 1. The control effectors are grouped into eight key groups: u_{lat}, u_{lon}, u_{dir}, cruise propeller throttle setting, cruise propeller RPM, cruise propeller blade pitch, lift propulsor RPMs, and lift propulsor blade pitches. The first three groups include the lateral, longitudinal, and directional control inputs from the FCS. The cruise propulsor RPMs N_{cp} are scheduled with respect to airspeed while the lift propulsor RPMs N_{1-8} are determined based on a set-point logic. The numbering of the lift propulsors is shown in Figure 5. In vertical flight mode, lift propulsor blade pitch is used for attitude control. The propulsor blade pitch settings are determined based on three blade pitch increments: β_ϕ, β_θ, and β_ψ. These increments are determined based on three corresponding wash-out variables K_{β_ϕ}, K_{β_θ}, and K_{β_ψ}. Lift propeller RPM is determined based on a set-point logic, which slowly varies the lift propeller RPM to restore the common lift propeller blade pitch, $\beta_{0,lp}$ to a pre-set target value. The elements of the matrix shown in the above equation were determined based on the normalized moment arm of each propulsor in the corresponding body-fixed axis.

$$\begin{bmatrix}\beta_1\\\beta_2\\\beta_3\\\beta_4\\\beta_5\\\beta_6\\\beta_7\\\beta_8\end{bmatrix} = \begin{bmatrix}1.00 & 1.00 & 0.43 & -0.54\\1.00 & 0.54 & 1.00 & 1.00\\1.00 & -0.54 & 1.00 & -1.00\\1.00 & -1.00 & 0.43 & 0.54\\1.00 & 1.00 & -0.43 & -0.54\\1.00 & 0.54 & -1.00 & 1.00\\1.00 & -0.54 & -1.00 & -1.00\\1.00 & -1.00 & -0.43 & 0.54\end{bmatrix}\begin{bmatrix}\beta_{0,lp}\\\beta_\phi\\\beta_\theta\\\beta_\psi\end{bmatrix}, \qquad \begin{Bmatrix}\beta_\phi = \beta_\phi^{max} u_{lat} K_{\beta_\phi}\\\beta_\theta = \beta_\theta^{max} u_{lon} K_{\beta_\theta}\\\beta_\psi = \beta_\psi^{max} u_{dir} K_{\beta_\psi}\end{Bmatrix} \qquad 9$$

The wash-out function K_β for the blade pitch variables is linear (as shown in Table 2), washing out the effect of the lift propulsors completely in forward flight for attitude control. Cruise propeller RPM N_{cp} is scheduled with airspeed per the schedule given in Table 2.

Table 2. Schedules (linear variations between data points)

KEAS	0	50	100	110	120	130	140	150	200+
$\boldsymbol{K_\beta}$	1	1	1	0.75	0.50	0.25	0	0	0
$\boldsymbol{N_{cp}}$	1200	2172	2200	2200	2200	2200	2200	2200	2200

Three normalized control variables u_{lat}, u_{lon}, and u_{dir} which range from [−1, +1], determine the control action for roll, pitch, and yaw. The control surface deflection commands are subject to the second-order actuator dynamics, deflection limits, and rate limits described in Table 3. The control allocation logic converts u_{lat}, u_{lon}, and u_{dir} to control surface deflections as follows:

$$\delta_{f1}, \delta_{f2}, \delta_{f3} = \delta_f^{max} u_{lat} \tag{10}$$

$$\delta_{f4}, \delta_{f5}, \delta_{f6} = -\delta_f^{max} u_{lat} \tag{11}$$

$$\delta_{e1}, \delta_{e2} = -\delta_e^{max} u_{lon} \tag{12}$$

$$\delta_{r1}, \delta_{r2} = \delta_r^{max} u_{dir} \tag{13}$$

Table 3. Control effector characteristics

Effector	**Symbol**	**Posn. limits** [deg]	**Rate limits** [deg/s]	**Nat. freq.** ω_n [rad/s]	**Damp. ratio** ζ [-]
Flaperons	$\delta_{f1} - \delta_{f6}$	± 30	± 60	75	0.7
Elevators	δ_{e1}, δ_{e2}	± 30	± 60	75	0.7
Rudders	δ_{r1}, δ_{r2}	± 30	± 60	42	0.7
Lift prop pitch	$\beta_1 - \beta_8$	$[-10, +18]$	± 30	75	0.7
Cruise prop pitch	β_{cp}	$[0, +42]$	± 5	30	1.2

3.2 Inceptor designs and inceptor mappings

The inceptors installed in the flight simulators as part of the AC and HC setups are shown in Figure 10.

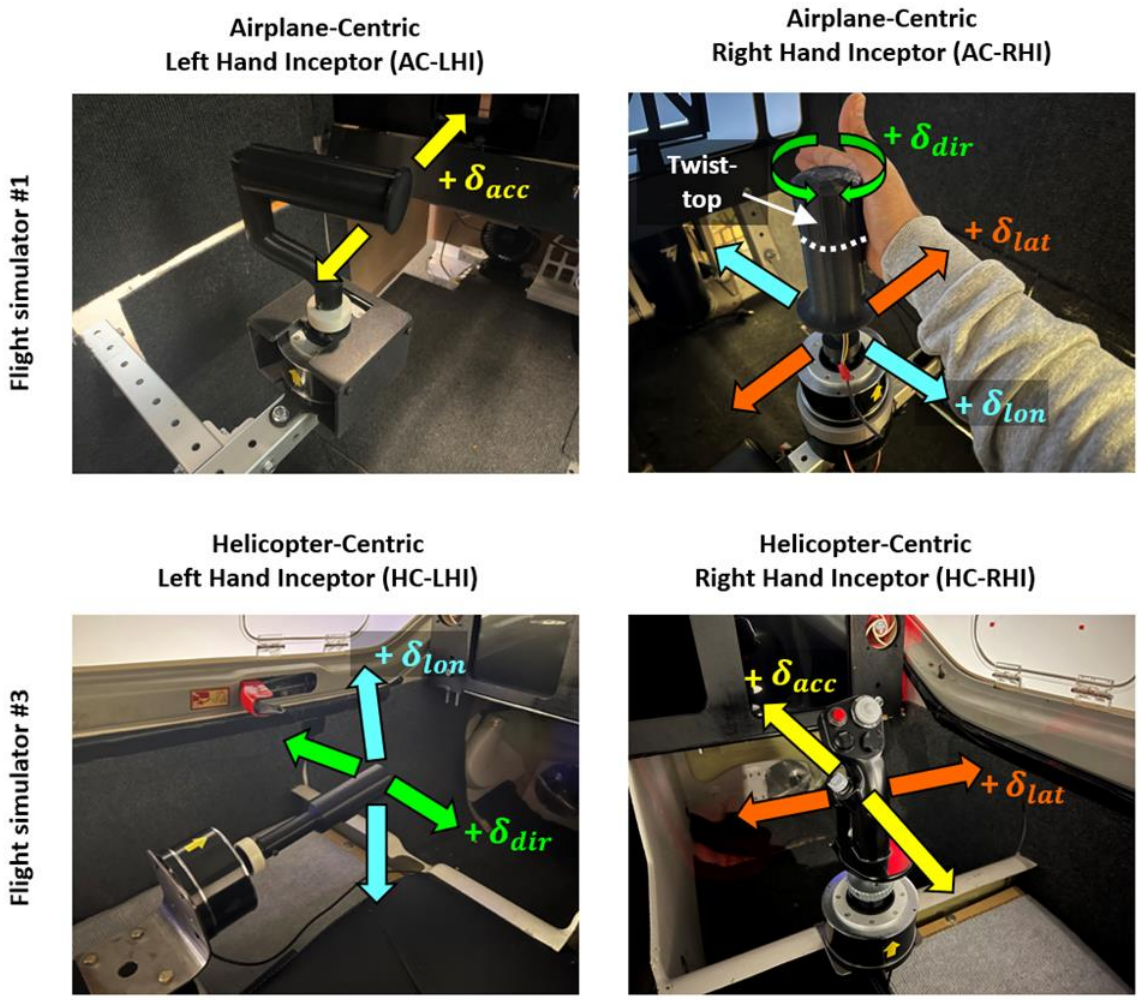

Figure 10. Inceptors for AC and HC setups

In each layout, there is a right-hand inceptor (RHI) and a left-hand inceptor (LHI). All four inceptors use the off-the-shelf Thrustmaster HOTAS Warthog™ Flight Stick as the base. The device has two axes, fore/aft and left/right, which are both spring-loaded to center. It has a detachable grip with multiple buttons, rocker switches, and four-way hat switches. The pilot inputs to the inceptors are captured as normalized signals for lateral input $\delta_{lat} \in [-1, +1]$, longitudinal input $\delta_{lon} \in [-1, +1]$, directional input $\delta_{dir} \in [-1, +1]$, and acceleration input $\delta_{acc} \in [-1, +1]$. The positive sense for each input is indicated in Figure 10 by a "+" sign.

For the AC setup:

- AC-LHI: The left/right degree-of-freedom of the base is blocked and a custom 3D-printed grip is installed onto the base. The fore/aft axis corresponds to the normalized acceleration input δ_{acc}. The inceptor is mounted such that the fore/aft movement is aligned with the cabin longitudinal axis.
- AC-RHI: The inceptor is mounted in a sidestick orientation and a custom grip is installed onto the base. The fore/aft motion of the inceptor corresponds to the normalized longitudinal input δ_{lon} and is aligned with the cabin longitudinal axis. The left-right motion corresponds to the normalized lateral input δ_{lat} and is aligned with the cabin lateral axis. The upper part of the custom grip, above the dotted line shown in Figure 10, incorporates a twisting element (called the "twist-top") whose twisting motion is picked up by a rotary potentiometer and fed into an Arduino microcontroller. The twist input corresponds to the normalized directional input δ_{dir}. When the inceptor is gripped by the right hand, the interface between the fixed lower part of the grip and the twist-top passes approximately through the center of the palm, as seen in Figure 10.

For the HC setup:

- HC-LHI: The inceptor is mounted similar to a helicopter collective control and has a simple 3D-printed cylindrical grip. Pulling vertically upward or pushing vertically downward generates the normalized longitudinal input δ_{lon}. While this motion is similar to that of a helicopter collective lever, the difference is that this axis is spring-loaded to center. Left/right movements of the HC-LHI are also possible (left: away from pilot's body, right: towards pilot's body), which generate the normalized directional input δ_{dir}.
- HC-RHI: The Warthog™ stick in unaltered form serves as this inceptor. The fore/aft motion generates the normalized acceleration input δ_{acc}, while the left/right motion generates the normalized lateral input δ_{lat}.

The inceptor-to-command mappings for AC and HC setups for VFM and FFM are summarized in Table 4. In FFM, centering both inceptors in Red Sim (HC setup) results in the aircraft returning to steady, level, unaccelerated flight. On the other hand, in Blue Sim (AC setup), it is possible to sustain steady climbing/descending and/or turning flight with both inceptors centered. For inceptor-to-command mappings that change between VFM and FFM, wash-in and wash-out functions are used to smoothly blend between VFM and FFM mappings.

3.2.1 Inceptor-to-command mappings

Table 4. VFM and FFM inceptor-to-command mappings for AC and HC setups

Input (symbol)	**Mode**	**Blue Sim (AC Setup)**	**Red Sim (HC Setup)**
Lateral (δ_{lat})		RHI side-to-side	RHI side-to-side
	VFM	Lateral velocity cmd	Bank angle cmd
	FFM	Roll rate cmd / bank hold	Bank angle cmd
Longitudinal (δ_{lon})		RHI fore-aft	RHI fore-aft
	VFM	Altitude rate cmd / Altitude hold	Altitude rate cmd / Altitude hold
	FFM	FPA rate cmd / FPA hold	Altitude rate cmd / Altitude hold
Directional (δ_{dir})		RHI twist	LHI side-to-side
	VFM	Heading rate cmd / Heading hold	Heading rate cmd / Heading hold
	FFM	Steady track sideslip	Steady track sideslip
Acceleration (δ_{acc})		LHI fore-aft	
	VFM	Speed rate cmd / Speed decay / Position hold	Speed rate cmd / Speed decay / Position hold
	FFM	Speed rate cmd / Speed hold	Speed rate cmd / Speed hold

3.2.2 Lateral axis

For Red Sim, the lateral input δ_{lat} generates a bank angle command ϕ_{cmd} directly in both VFM and FFM, with no mode blending. The command is generated as follows:

$$\frac{\phi_{cmd}}{\delta_{lat}}(s) = \frac{\phi_{max}}{\tau_{lat}s+1} \qquad 14$$

The time constant is fixed at τ_{lat} = 0.2. The maximum bank angle ϕ_{max} is limited to 15° below 40 knots and 55° above 50 knots, with a linear ramp-up between 40 and 50 knots.

For Blue Sim, the lateral input δ_{lat} generates a lateral velocity command in VFM and a roll rate command in FFM. The lateral velocity command v_{cmd} in VFM is generated as follows:

$$\frac{v_{cmd}}{\delta_{lat}}(s) = \frac{v_{cmd,max}}{\tau_{lat}s+1} \qquad 15$$

The maximum lateral velocity command is limited to 20 knots. PI control on the lateral velocity error is then used to generate a bank angle command $\phi_{cmd,VFM}$. In FFM, the lateral input δ_{lat} generates a roll rate command $\dot{\phi}_{cmd,0}$ as follows:

$$\frac{\dot{\phi}_{cmd,0}}{\delta_{lat}}(s) = \frac{\dot{\phi}_{cmd,max}}{\tau_{lat}s+1} \quad 16$$

The maximum roll rate command is $\dot{\phi}_{cmd,max} = 40$ deg/s. The net roll rate command is then synthesized as $\dot{\phi}_{cmd} = \dot{\phi}_{cmd,0} + \dot{\phi}_{cmd,dih}$.

The second term, of the form $\dot{\phi}_{cmd,dih} = -K\phi$, represents an artificial dihedral stability effect that is effective (i) at steep bank angles $|\phi| > 45°$, (ii) at low bank angles $|\phi| < 10°$, and (iii) for all bank angles during transition between VFM and FFM in the speed range 40-140 knots.

The roll rate command is integrated to give a FFM bank angle command $\phi_{cmd,VFM}$. The net bank angle command is then synthesized as

$$\phi_{cmd} = \zeta_{lat}\phi_{cmd,VFM} + (1-\zeta_{lat})\phi_{cmd,FFM} \quad 17$$

where ζ_{lat} is a wash-out variable, with $\zeta_{lat} = 1$ below 40 knots, $\zeta_{lat} = 0$ above 50 knots, and with linear wash-out in the 40-50 knot range.

3.2.3 Longitudinal axis

In Red Sim, the longitudinal input δ_{lon} generates a vertical velocity command in both VFM and FFM, as follows

$$\frac{\dot{h}_{cmd}}{\delta_{lon}}(s) = \frac{\dot{h}_{cmd,max}}{\tau_{lon}s+1} \quad 18$$

with $\tau_{lon} = 0.02$ and a maximum vertical velocity command of $\dot{h}_{cmd,max} = 1{,}500$ ft/min.

For Blue Sim, vertical velocity command generation in VFM follows the equation above. In FFM, the longitudinal input δ_{lon} generates a flightpath angle rate command as

$$\frac{\dot{\gamma}_{cmd}}{\delta_{lon}}(s) = \frac{\dot{\gamma}_{cmd,lim}(V)}{\tau_{lon}s+1} \quad 19$$

where the flightpath angle rate command limit $\dot{\gamma}_{cmd,lim}(V)$ is set with speed to limit steady-state load factor to the range $n \in [0,3.8]$ based on the relationship $\dot{\gamma} = (180/\pi)(g/V)(n-1)$. The flightpath angle rate command is integrated to yield the flightpath command γ_{cmd}. The corresponding vertical velocity command for FFM is synthesized as $\dot{h}_{cmd,FFM} = V\sin\gamma_{cmd}$. The net vertical velocity command is then synthesized as

$$\dot{h}_{cmd} = \zeta_{lon}\dot{h}_{cmd,VFM} + (1-\zeta_{lon})\dot{h}_{cmd,FFM} \quad 20$$

where ζ_{lon} is a wash-out variable, with $\zeta_{lon} = 1$ below 140 knots, $\zeta_{lon} = 0$ above 150 knots, with linear wash-out in the 140-150 knot range. For Blue Sim, the derivative of the vertical velocity command, $\ddot{h}_{cmd}$ is used in a feed-forward path to quicken the TECS algorithm response, see Comer & Chakraborty (2023). It is calculated as $\ddot{h}_{cmd} = V\ddot{h}_{cmd}\cos\gamma_{cmd}$.

3.2.4 Directional axis

The directional inceptor-to-command mapping is identical for both Blue Sim and Red Sim. In VFM, the directional input δ_{dir} generates a yaw rate command as

$$\frac{r_{cmd}}{\delta_{dir}}(s) = \frac{r_{cmd,max}}{\tau_{dir}s+1} \tag{21}$$

with $\tau_{dir} = 0.02$, and the maximum yaw rate command set to $r_{cmd,max} = 22$ deg/s based on ADS-33E-PRF performance requirements for level 1 moderate agility (United States Army, 2000). For FFM, the directional input δ_{dir} generates a sideslip command as

$$\frac{\beta_{cmd}}{\delta_{dir}}(s) = \frac{\beta_{cmd,max}}{\tau_{dir}s+1} \tag{22}$$

with the maximum sideslip command set to $\beta_{cmd,max} = 15°$. The yaw rate command in FFM is generated as

$$r_{cmd,FFM} = \frac{g}{V}\cos\gamma\sin\phi_{cmd} - K_{n_y}n_y, \qquad \delta_{dir} = 0 \tag{23}$$

$$r_{cmd,FFM} = \frac{g}{V}\cos\gamma\sin\phi_{cmd} - K_{\beta}(\beta_{cmd} - \beta), \qquad \delta_{dir} \neq 0 \tag{24}$$

The above logic attempts to coordinate the turn ($n_y = 0$) if no directional input is applied, i.e., $\delta_{dir} = 0$. However, if directional input is applied, i.e., $\delta_{dir} \neq 0$, a yaw rate proportional to the sideslip error is commanded. In both cases, the yaw rate required for a coordinated turn at the commanded bank angle is also applied. The net yaw rate command is synthesized as

$$r_{cmd} = \zeta_{dir}r_{cmd,VFM} + (1 - \zeta_{dir})r_{cmd,FFM} \tag{25}$$

where ζ_{dir} is a wash-out variable, with $\zeta_{dir} = 1$ below 40 knots, $\zeta_{dir} = 0$ above 50 knots, with linear wash-out in the 40-50 knot range.

3.2.5 Acceleration inputs

The mapping of the acceleration input δ_{acc} is common for both Blue Sim and Red Sim. In VFM, the acceleration input generates an acceleration command (in g), with a velocity dissipation effect. A basic acceleration command is first generated as

$$\frac{a_{cmd,0}}{\delta_{acc}}(s) = \frac{a_{max}}{\tau_{acc}s+1} \tag{26}$$

with time constant $\tau_{acc} = 0.03$ and maximum acceleration $a_{max} = 0.2g$. The velocity dissipation effect is intended to dissipate velocity to zero (hover) if the input is neutralized ($\delta_{acc} = 0$). It is modeled as $a_{diss} = -K_{diss}|V|sgn(V)$, with the dissipation gain $K_{diss} = 0.017$. The VFM acceleration command is then synthesized as $a_{cmd,VFM} = a_0 + a_{diss}$. In FFM, the acceleration input generates a dimensional acceleration as

$$\frac{\dot{V}_{cmd}}{\delta_{acc}}(s) = \frac{K_{\dot{V}} g}{\tau_{acc} s + 1} \qquad 27$$

with $K_{\dot{V}} = 0.6$. This is integrated to form the velocity command V_{cmd}. The FFM acceleration command is then synthesized as

$$a_{cmd} = \zeta_{acc} a_{cmd,VFM} + (1 - \zeta_{acc}) a_{cmd,FFM} \qquad 28$$

where ζ_{acc} is a wash-out variable, with $\zeta_{acc} = 1$ below 25 knots, $\zeta_{acc} = 0$ above 35 knots, with linear wash-out in the 25-35 knot range.

3.3 Cockpit displays

Both Blue Sim (Figure 1) and Red Sim (Figure 2) have different cockpit dimensions and the make/model of the cockpit display units, but the appearance of displays is standardized through the design of panel facade pieces. The visible screen areas for both simulators are identical, and they have identical display element layouts. Each panel is built up of a left display, a center display, a right display, a Garmin Pilot™ based moving map display, and a screen displaying a downward-looking camera view to aid in landing.

3.3.1 Primary flight display (PFD)

At the center of the cockpit display, lies the primary flight display (PFD), shown in Figure 11.

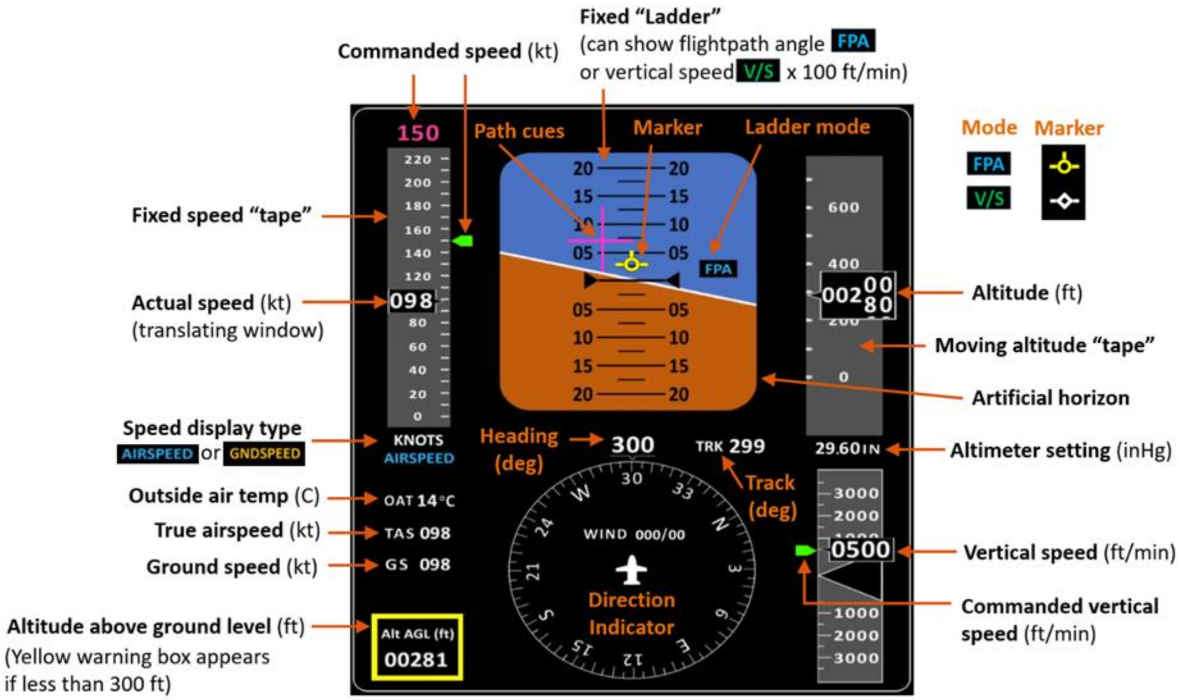

Figure 11. Primary flight display

It represents important information regarding current flight conditions. Airspeed is indicated on the left side using a fixed tape, over which translates a moving bogey with a speed readout. The type of speed is displayed below the tape by a text readout AIRSPEED or GNDSPEED. A translating green marker on the right side of the tape shows the commanded speed with a text readout appearing at the top of the tape.

The right side of the PFD has a fixed textbox and a translating tape behind the textbox which gives the altitude readout. Vertical velocity is shown below the altitude tape by a translating bogey with a vertical speed readout. A green marker shows the commanded vertical velocity (altitude rate). Heading, track, and wind information are presented in the lower part of the PFD.

The artificial horizon is used to provide a general idea of the pitch and bank attitudes to the pilot during flight. Since the pilot control inputs are provided in terms of either vertical velocity or FPA (through FPA rate), a *fixed* ladder is incorporated that indicates FPA (in degrees) as well as vertical velocity (in hundreds of feet per minute). A yellow flightpath marker and a FPA readout appear in FFM to indicate that FPA information is being displayed. The flightpath marker turns to a white diamond shape in the VFM, and a V/S text readout appears to show the vertical speed. If vertical or lateral guidance modes are engaged, a magenta + sign appears on the PFD. The magenta guidance and the flightpath markers can move up/down and left/right. This makes the necessary control action more intuitive for the pilots, as they need to fly the flightpath marker to the location of the magenta guidance symbol

3.3.2 Other display elements

The other cockpit display elements incorporated into the simulators are the following:

- **Auto-Flight panel** (Figure 12):

  Actions such as takeoff, transition to forward flight, transition to vertical flight, hover, and landing can be selected, sequenced, or initiated through individual buttons using the auto-flight panel. The *Flight Director/ Navigation* (FD/NAV), generates vertical navigation (VNAV), lateral navigation (LNAV), and speed (SPD) cues on the PFD. These can be tracked manually by the pilot or automatically by the FCS if VNAV, LNAV, and SPD modes are engaged.

- **Inceptor position and control law display** (Figure 13A):

  The inceptor positions and inceptor mappings currently in effect are displayed on this panel. VFM and FFM are represented using white and blue texts respectively. If mode transitions are associated with control law blending, both VFM and FFM mappings are displayed as long as the blend is active.

- **Control effort and saturation indicator** (Figure 13B):

  The current control effort is indicated for roll, pitch, and yaw axes as well as forward and vertical thrust. Saturation (or near saturation) of any of the controls is indicated by a SAT flag readout.

- **Synoptic display:**

  This shows the states of all control effectors, including positions of control surfaces as well as RPM and blade pitch of cruise and lift propellers as shown in Figure 14.

- **Operating mode indicator:**

  This indicates whether the aircraft is in FLIGHT or GROUND mode. Switches between the two modes are possible only when the vehicle is in ground contact, and are triggered by a 5-second-long full deflection of longitudinal inceptor in the direction commanding a descent.

- **Battery state-of-charge indicator:**

  This indicates the battery state-of-charge, instantaneous power consumption, and remaining flight time at the current power setting, including the hover power setting.

- **Landing camera:**

  This aids the pilot in landing. When descending, the look-down angle of the camera tracks the aircraft FPA , and at lower speeds, the camera points vertically down.

- **Moving map:**

  Garmin Pilot™ application is used to display the moving map by driving the ownship symbol with the aircraft trajectory after interfacing with X-Plane.

- **Taxi map and checklist display:**

  This is used to display a taxi map of the vertiport and also relevant checklists. This display was used to describe each piloting task to study participants in this work.

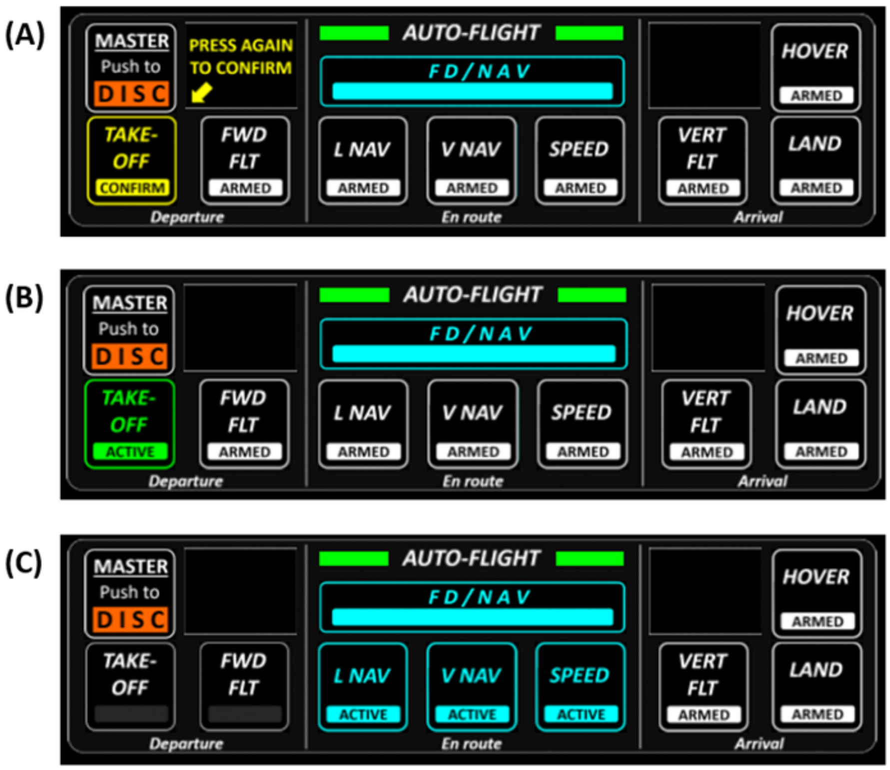

Figure 12. Auto-flight panel

(A) all automatic modes armed, vertical takeoff confirmation requested (B) vertical takeoff mode active (C) en-route automatic navigation, vertical takeoff, and forward flight transition completed

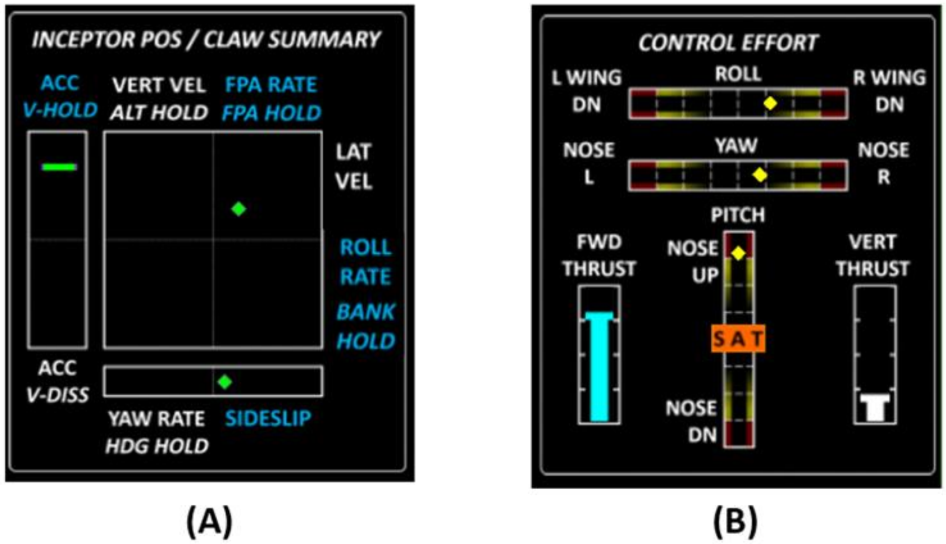

Figure 13. (A) Inceptor positions and control law summaries (B) Control effort and control margin awareness

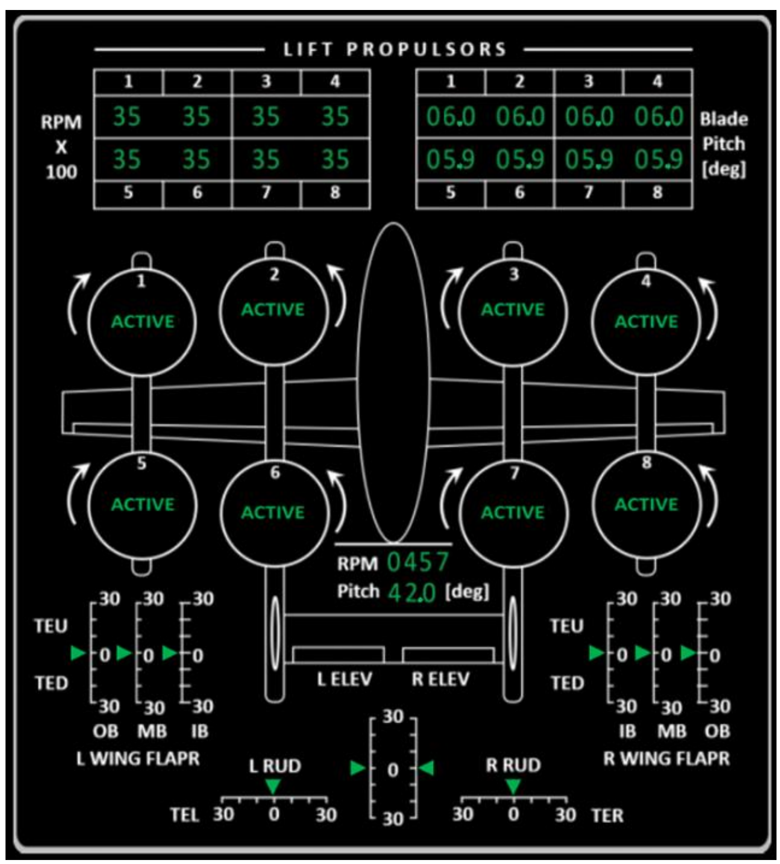

Figure 14. Synoptic Display

4 Design of piloted simulation experiments

4.1 Participant recruitment and flight experience

Participants were recruited through informational flyers about the project that were disseminated through e-mailing lists to the Department of Aerospace Engineering and the School of Aviation at Auburn University. Per the study protocol approved by the Auburn University Institutional Review Board (IRB), individuals who agreed to participate in the study by signing an informed consent form were de-identified by assigning an alphanumeric identifier corresponding to their group (e.g., A1, B5, etc.).

Collected data from participants was linked only to their alphanumeric identifiers. All Group A participants and all but one Group B participant were recruited from the School of Aviation at Auburn University (the remaining Group B participant was recruited from the Department of Aerospace Engineering). They were required to fill out a pilot experience summary form to capture relevant information about their flight experience.

The ratings and certificates of participants include: Certified Flight Instructor (CFI), Certified Flight Instructor - Instrument (CFII), Commercial Pilot License, Multi-Engine Land (CMEL), Commercial Pilot License, Single-Engine Land (CSEL), Instrument rating (IR), Private Pilot License (PPL), Remote Pilot Certificate (RPC), Student Pilot Certificate (SPC). A total of five Group A participants (aviators holding instructor certificates) were recruited. Their flight experience is summarized in Table 5.

Table 5. Group A participant flight experience (* indicates undergoing training)

Identifier	**Certificates and Ratings**	**PIC hours**	**Aircraft**
A4	PPL, IR, CSEL, CMEL, CFI, CFII*	615	C172, AA5B. P28A. C152
A5	PPL, IR, CSEL, CMEL, CFI, CFII	477	C172
A6	PPL, IR, CSEL, CMEL, CFI, CFII*	337	C172, PA44
A7	PPL, IR, CSEL, CMEL, CFI, CFII*	755	C172, BDOG, P28A, PA44, DA40, RV7, C150, PA23
A8	PPL, IR, CSEL, CMEL, CFI, CFII*	269	C172, P28A

They reported between 269 and 755 pilot-in-command (PIC) hours in a variety of fixed-wing aircraft. Four of them were currently undergoing training for a Certified Flight Instructor - Instrument (CFII) certificate, which the fifth already held. None of them reported any rotorcraft experience and none held an Airline Transport Pilot (ATP) certificate or a Multi-Engine Instructor (MEI) rating. A total of nine Group B participants (licensed pilots and/or students undergoing any flight training) were recruited. Their flight experience is summarized in Table 6.

Table 6. Group B participant flight experience (* indicates undergoing training)

Identifier	**Certificates and Ratings**	**PIC hours**	**Aircraft**
B1	PPL, IR, CMEL*, RPC	283	C172, C152, P28A, PA44
B3	SPC, PPL*	3	C172
B4	PPL, IR, CMEL*	214	C172
B5	PPL, IR, CMEL*	240	C172
B6	PPL, IR, CMEL*, RPC	192	C172, PA44
B7	PPL, IR, CMEL*, RPC	138	C172, C150
B8	SPC, PPL*	9	C172
B9	PPL, IR, CSEL, CMEL, RPC	1209	C172, PA46, SR22, 7GCBC, BE58, BE76, P28A, C240
B10	PPL, IR, CSEL*, CMEL*	223	C172, C182, DA40, P28A

Two individuals were undergoing primary training, seven held instrument ratings, six were undergoing training toward a commercial pilot license, and four held remote pilot certificates. Their PIC experience ranged from 3 hours to 1209 hours, logged in a variety of fixed-wing aircraft. A total of seven Group C participants (individuals without pilot licenses or any pilot training) were recruited, all from the Department of Aerospace Engineering. Since they lacked any flight experience, the pilot experience summary form was not applicable to them. Their alphanumeric identifiers were assigned as C1, C4, C5, C6, C7, C8, and C10. In total, twenty-one participants across the three groups took part in the simulation campaign, which occurred between October 17, 2022 and December 2, 2022.

4.2 Preparatory instructional material

Before their arrival, the participants were provided access to instructional videos prepared by the research team for both Blue Sim and Red Sim in the form of unlisted YouTube videos[1].

The videos, customized for each simulator, contained the following elements in order:

- a description of the LPC-03 Phoenix configuration, explaining the roles of the control effectors in VFM and FFM,
- a labeled image showing the cockpit display elements (see Figure 1 for Blue Sim and Figure 2 for Red Sim),
- a more detailed description of the PFD elements,
- a demonstration of the axes of motion of the RHI and LHI of each simulator,
- demonstration of ground taxiing in GROUND mode and switching between GROUND mode and FLIGHT mode,
- demonstration of how to maneuver the aircraft in VFM along the heave, fore/aft, lateral, and directional axes,
- demonstration of how to climb/descend, turn, and accelerate/decelerate in FFM, and
- demonstration of transitioning from VFM to FFM (departure transition) and from FFM to VFM (arrival transition).

In the demonstration video segments, a time-synchronized split screen layout was utilized, showing an "over-the-shoulder" view looking out front, a zoomed-in view of the relevant inceptor(s) being manipulated, an external visualization of the aircraft (in X-Plane), and the PFD. The narration in these videos avoided technical jargon pertaining to flight control laws and inceptor mappings. Instead, the narration provided a general description associating pilot inputs along each inceptor axis with the resulting general response of the aircraft. No comments were made in either video comparing or contrasting the response of Blue Sim and Red Sim to the same pilot inputs. This was left for participants to infer.

[1] Blue Sim Video: https://www.youtube.com/watch?v=D-M-Zs26Xfs

Red Sim Video: https://www.youtube.com/watch?v=HHlrVYNM1yg

4.3 Simulation task descriptions

Participants made one visit to Blue Sim and one to Red Sim. These were required to be on different days to avoid fatigue and overload. Of the twenty-one participants, ten experienced Blue Sim on their first visit, while the remaining eleven experienced Red Sim on their first visit. Each visit was scheduled to be three hours long, following the activity schedule shown in Table 7. Participants were compensated for their time at $50/hour. Upon each participant's arrival for their first visit, the pilot experience summary form was collected, and the alphanumeric identifier was assigned. The participant's seating height in the simulators was adjusted to give a consistent eye-point height across all participants.

Table 7. Activity schedule for Blue Sim and Red Sim simulation sessions

Item	**Time allocation (min)**	**Cumulative time (min)**
Data collection & ID assignment	5	5
Eye-point calibration	5	10
“Free flight” for VFM	5	15
“Free flight” for FFM	5	20
Vertical reposition & hold	15	35
Hovering turn & hold	15	50
(Mini-break)	5	55
Lateral reposition & hold	20	75
Pirouette	20	95
Precision hover	20	115
(Mini-break)	5	120
Transition to forward flight	20	140
UAM mission & heliport approach	20	160
(Buffer time)	20	180

While seated in the simulator and before performing each simulation task, participants listened to an audio description of the task. These audio clips familiarized the participants with the HQTE courses by explaining the significance of the hover boards, reference markings, and objects as well as establishing the objectives or targets of each simulation task. The checklist display (see Figure 1 and Figure 2) was used to allow participants to play, stop, and repeat the audio clips.

The free flights for VFM and FFM required the participants to perform single-axis maneuvering tasks to familiarize them with the response of Blue Sim and Red Sim to inputs along each inceptor axis. They were free in the sense that no precision targets were assigned to these introductory tasks. After completing these, the participants progressed sequentially through the following HQTEs, which were arranged in increasing levels of anticipated difficulty:

1. Vertical reposition and hold is shown in Figure 15.
2. Hovering turn and hold is shown in Figure 18.
3. Lateral reposition and hold is shown in Figure 21.
4. Pirouette is shown in Figure 24.
5. Precision hover is shown in Figure 27.

The HQTEs were modeled based on *Handling Qualities Task Element Draft Version 1.0*, submitted with cover letter to members of the eVTOL Flight Test Council by Klyde et al. (2021). In addition to the above, a flight profile representing a UAM mission (Figure 30) comprising takeoff and transition while clearing an obstacle, en-route navigation, and landing approach over an obstacle, was also simulated. The suggested courses for these HQTEs were modeled and then deployed within the Blue Sim and Red Sim visual environment, as shown in Figure 36.

4.4 Data collection

For each simulation run, the data logged by the MADCASP framework included aircraft motion states, control effector states, inceptor signals, and commands generated within the FCS architecture (Figure 6). Following each simulation task, participants (while still seated in the simulator) filled out a task workload questionnaire electronically. The goal of this questionnaire was to elicit information from each participant that would allow a Cooper-Harper rating (CHR) to be calculated after-the-fact, even if the participants themselves were unfamiliar with the CHR scale. The questions that were asked in the questionnaire and the calculation of CHR are explained in Appendix B. The scale itself is presented in Figure B- 1. The questionnaire also had text-boxes for each question to collect optional descriptive comments from the participants. The pilot experience summary (if applicable), logged simulator data, and task workload questionnaire data for each task constituted the entirety of the data collected from participants for this study.

5 Piloted simulation results

The piloted simulation sessions generated, in addition to aircraft and control system state data logged from MADCASP, participant feedback for each simulated task collected using the task workload questionnaire. The responses and comments of each participant for each simulation task in each simulator are provided in Appendix C. The following sections provide selected results, aggregate statistics, observations, and insights obtained from studying the collected data.

5.1 Vertical reposition and hold

This HQTE starts from a stabilized hover, and requires the initiation of a vertical ascent of 25 ft, stabilization at the new altitude for 5 seconds, followed by a descent back to and stabilization at the original hover altitude. The goal is to check for acceptable heave damping that allows a vertical rate to be started and stopped with precision, check for any pilot-induced oscillation tendencies, and any undesirable coupling between the heave axis inceptor and others. A suggested course for this HQTE is shown in Figure 15. The details of the performance requirements for this HQTE are shown in Table 8.

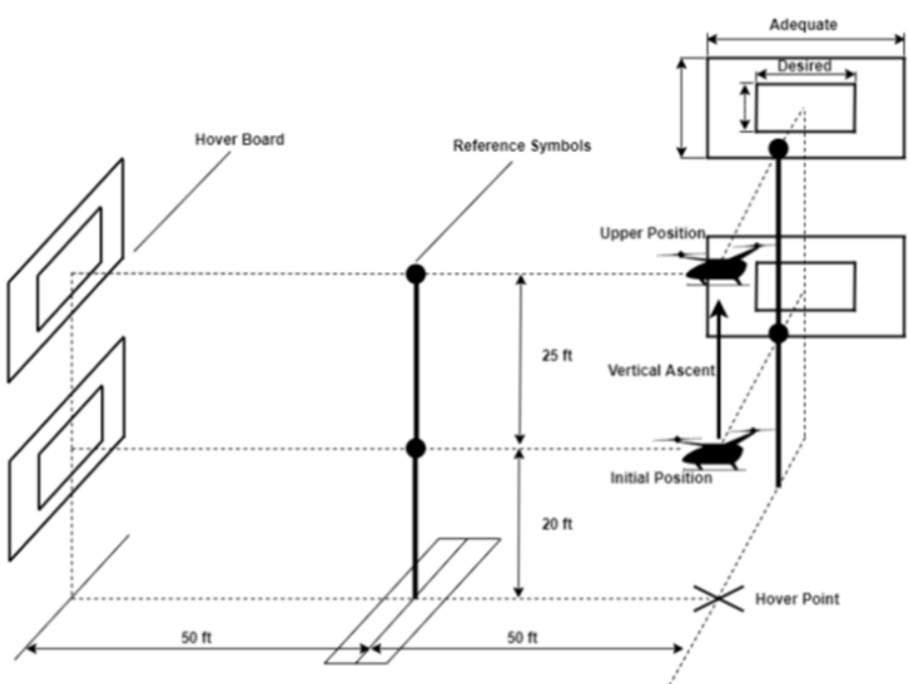

Figure 15. Suggested course for vertical reposition and hold HQTE

Table 8. Performance requirements for vertical reposition and hold HQTE

Task Performance Requirements	**Desired**	**Adequate**
Maintain longitudinal and lateral position within ±X from the hover point	± 3 ft	± 6 ft
Maintain start/finish altitude within ± X	± 3 ft	± 6 ft
Maintain heading within ± X Complete maneuver within X	± 5 deg ≤ 20-24 s	± 10 deg ≤ 25-29 s
PIO tendencies in the capture and hold	No undesirable motions that impact task performance	No PIO (out-of-phase oscillations)

The derived CHR for the vertical reposition and hold HQTE are shown in Figure 16 and aggregate statistics are provided in Table 9. The mean CHR across all participants was 3.2 for Blue Sim and 2.1 for Red Sim. Based on the computed CHR for this HQTE, 57.1% rated Blue Sim as Level 1 and 80.9% rated Red Sim as Level 1.

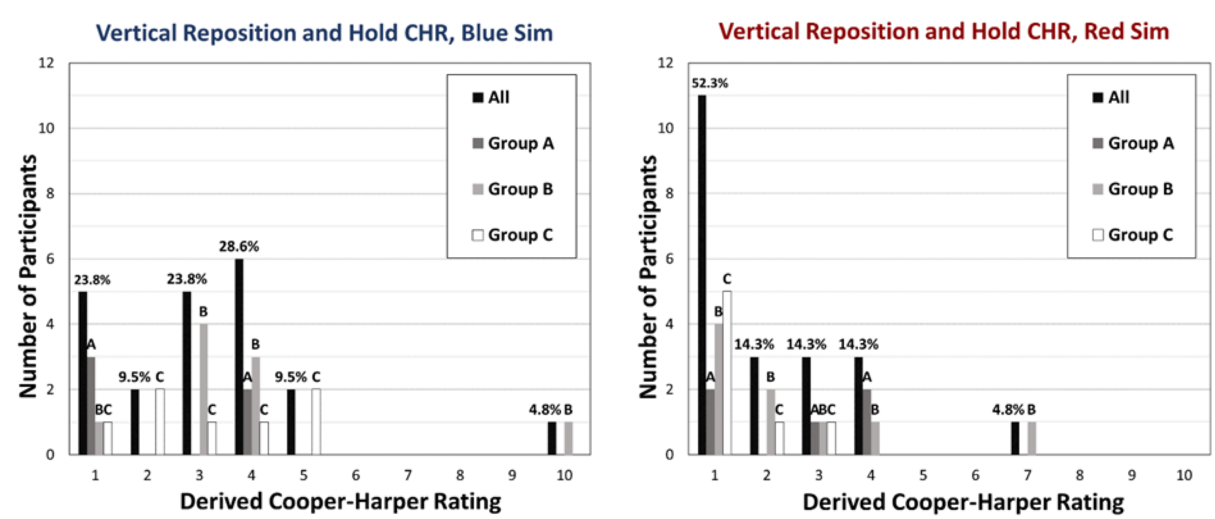

Figure 16. Vertical repositioning Cooper-Harper Rating

Table 9. Derived Cooper-Harper ratings for HQTEs

HQTE	Simulator	Group A	Group B	Group C	Overall
Vertical reposition and hold	Blue	2.2 (1.5)	3.9 (2.3)	3.1 (1.5)	3.2 (2.0)
	Red	2.6 (1.4)	2.4 (1.9)	1.4 (0.7)	2.1 (1.6)
Hovering turn and hold	Blue	1.6 (1.2)	1.3 (0.7)	1.7 (0.7)	1.5 (0.9)
	Red	2.6 (1.6)	1.8 (0.9)	2.4 (1.4)	2.2 (1.3)
Lateral reposition and hold	Blue	2.4 (1.4)	3.6 (1.2)	3.9 (1.6)	3.4 (1.5)
	Red	5.2 (2.1)	4.6 (2.1)	5.1 (3.2)	4.9 (2.5)
Pirouette	Blue	3.0 (1.8)	3.4 (2.4)	3.7 (3.1)	3.4 (2.5)
	Red	3.6 (2.0)	4.4 (3.2)	4.0 (3.4)	4.1 (3.1)
Precision hover	Blue	2.4 (1.4)	3.7 (2.6)	3.3 (2.2)	3.2 (2.3)
	Red	3.4 (2.1)	3.4 (1.1)	3.3 (2.4)	3.4 (1.9)
Takeoff and VFM-FFM transition	Blue	2.7 (1.5)	2.2 (1.5)	3.0 (1.6)	2.6 (1.3)
	Red	1.9 (1.0)	2.2 (1.2)	1.6 (0.7)	2.0 (1.2)
FFM-VFM transition and landing	Blue	3.6 (2.3)	3.0 (0.9)	3.4 (1.9)	4.3 (3.1)
	Red	4.1 (3.4)	3.8 (3.2)	3.9 (2.8)	4.6 (4.1)

The most notable observations identified based on the review of the individual comments for this HQTE (see Appendix C) are as follows:

- Nine participants reported inadvertent cross-coupling of inceptor inputs in Blue Sim for this HQTE. While attempting to control vertical axis motion with fore/aft movements of the RHI, unintended lateral inputs to the RHI caused the aircraft to drift laterally. For Red Sim, where up/down movements of the LHI control vertical axis motion and left/right movements control yaw, no participants reported unintended coupling of yawing motion.
- Several participants noted that this HQTE was "easy" in Red Sim. One participant further commented that it was "easier" in Red Sim than in Blue Sim.
- For both simulators, some participants mentioned excessive control sensitivity, making it easy to over-correct.

A comparison of the performance of one participant (A4) for the vertical reposition and hold HQTE in Blue Sim and Red Sim is shown in Figure 17. The desired and adequate performance for this HQTE are described in Table 8.

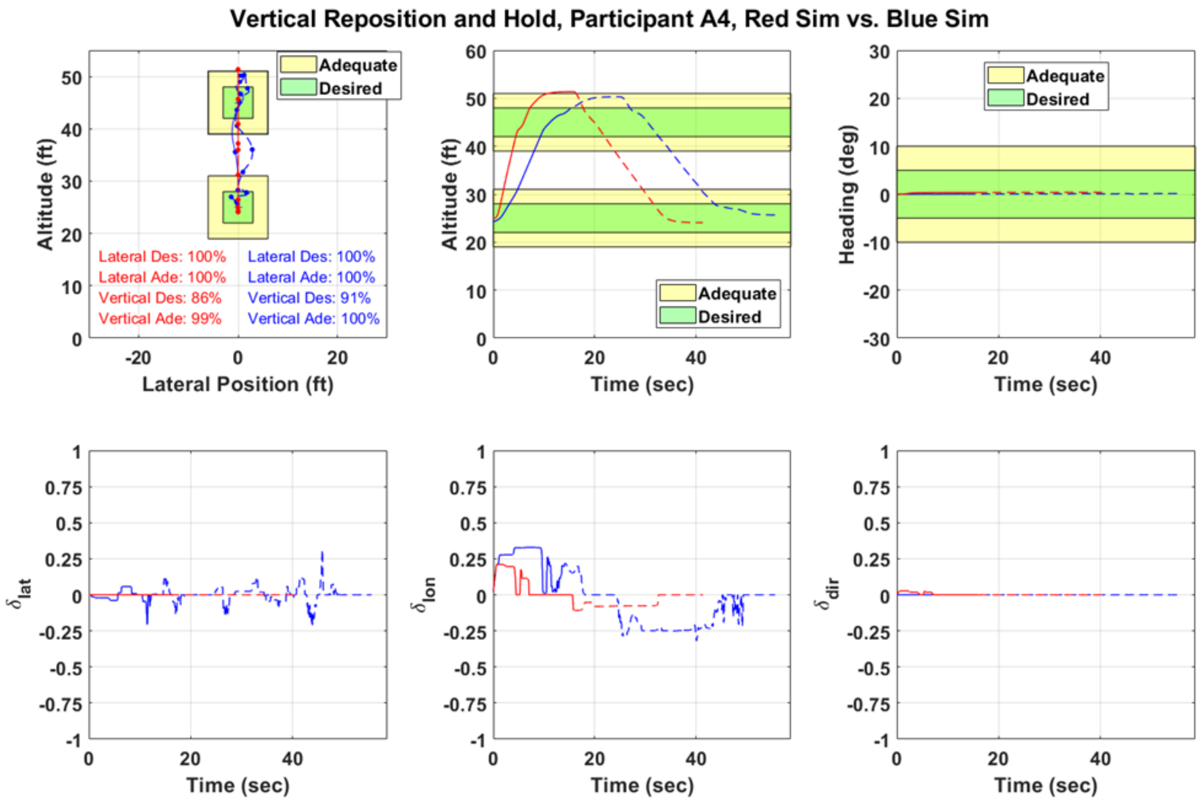

Figure 17. Vertical reposition and hold, Participant A4, Blue Sim vs. Red Sim

However, participants were not given any time targets within which to complete the maneuver. In both simulators, the participant remains within the desired lateral bounds 100% of the time (and thereby, within adequate bounds 100% of the time, as well). When performing the ascent, the participant overshoots the desired altitude band in both Blue Sim and Red Sim and settles into a hover slightly above it. Coupling between longitudinal and lateral RHI inputs in Blue Sim is evident from the lateral trajectory of the aircraft and the time history of lateral control input δ_{lat}. While controlling the vertical axis motion in Blue Sim (δ_{lon}, RHI fore/aft), the participant inadvertently couples this input with lateral input (δ_{lat}, RHI left/right), and subsequently has to correct. In Red Sim, such coupling is not seen, as different hands control vertical axis motion (δ_{lon}, LHI up/down) and lateral axis motion (δ_{lat}, RHI left/right). The Red Sim directional input (δ_{dir}, LHI left/right) shows a very slight initial coupling with the vertical axis input, but the effect on the heading is not significant. The desired heading discipline was achieved 100% of the time for both simulators. The desired and adequate performances in the lateral and vertical directions for this HQTE of all the participants are shown in Table 10.

Table 10. Desired and adequate performance for vertical reposition and hold (all participants)

Participant ID	Blue Sim				Red Sim			
	Performance Lateral (%)		Performance Vertical (%)		Performance Lateral (%)		Performance Vertical (%)	
	Desired	**Adequate**	**Desired**	**Adequate**	**Desired**	**Adequate**	**Desired**	**Adequate**
A4	100	100	86	99	100	100	91	100
A5	100	100	66	79	100	100	83	100
A6	98	100	76	100	100	100	83	95
A7	100	100	51	100	100	100	53	97
A8	100	100	76	100	100	100	83	100
B1	81	97	58	100	100	100	68	100
B3	91	100	68	100	100	100	85	100
B4	100	100	78	100	98	100	63	75
B5	74	95	72	100	100	100	87	100
B6	86	98	63	81	100	100	73	78
B7	100	100	82	91	100	100	76	100
B8	74	100	85	100	100	100	89	100
B9	98	100	68	84	100	100	88	100
B10	100	100	84	100	100	100	90	100
C1	100	100	71	91	100	100	91	100
C4	82	100	75	86	100	100	86	94
C5	100	100	81	100	100	100	81	100
C6	100	100	65	100	100	100	85	100
C7	100	100	60	75	100	100	84	100
C8	68	93	71	83	100	100	86	93
C10	92	100	79	100	100	100	87	100

5.2 Hovering turn and hold

Starting from a stabilized hover, a 90° turn to one side must first be completed while maintaining a hover position. After holding the new heading for 5 seconds, a 270° turn in the same direction must be performed to return to and stabilize at the original heading. The sequence must then be repeated while turning in the other direction. The goals are to check for undesirable handling qualities or inter-axis coupling and the ability to initiate and dissipate hover turn rates with precision. The suggested course for hovering turn and hold is shown in Figure 18. The details of the performance requirements for this HQTE are shown in Table 11.

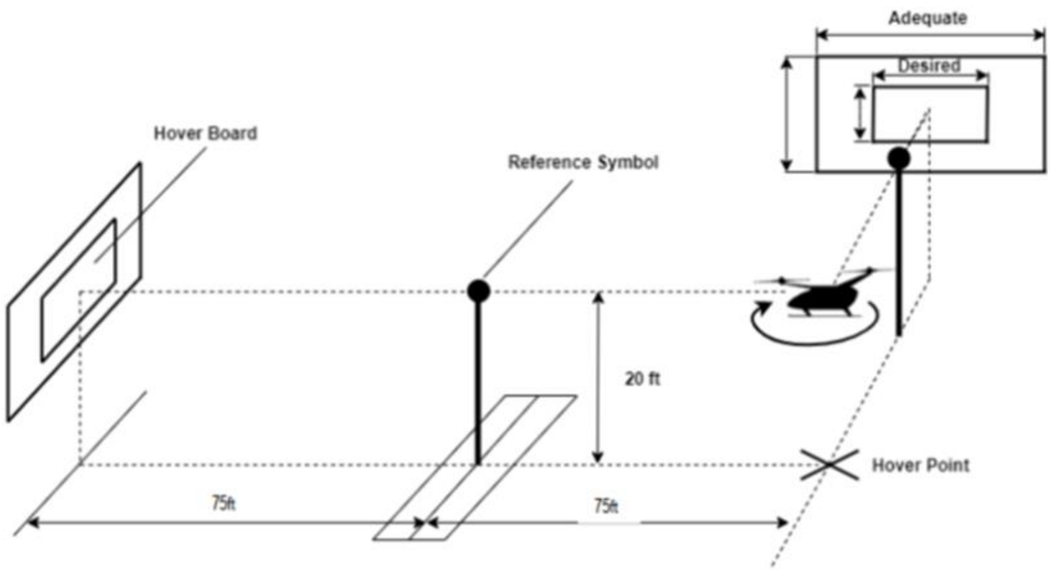

Figure 18. Suggested course for hovering turn and hold HQTE

The derived CHR for the hovering turn and hold HQTE are shown in Figure 19 and aggregate statistics are provided in Table 9. The mean CHR computed for this HQTE was 1.5 for Blue Sim and 2.2 for Red Sim. 95.2 % of participants rated Blue Sim as Level 1 for this HQTE, while 76.2% did so for Red Sim.

The most notable observations identified based on the review of the individual participant comments for this HQTE (see Appendix C) are as follows:

- Eight participants reported inadvertent cross-coupling of inceptor inputs in Red Sim for this HQTE. As they attempted to control the heading/yaw of the aircraft using left/right movements of the LHI, unintentional up/down inputs to the LHI resulted in movement along the vertical axis. No such coupling was reported between the twist axis of the Blue Sim RHI and the fore/aft and left/right axes of that inceptor.

- One participant commented that the ergonomics of the Blue Sim RHI twist-top could be improved. Three participants commented that the Blue Sim aircraft felt different when yawing to the left versus the right. This may have been due to some “stickiness” in the twist-top which differed between left and right directions.

- One participant wished that there was some displayed indication of roll rate and turn rate during the maneuver. Two participants commented that it was easier to perform this HQTE in Red Sim, while one commented that it was easier to do in Blue Sim.

Table 11. Performance requirements for hovering turn and hold HQTE

Task Performance Requirements	**Desired**	**Adequate**
Maintain longitudinal and lateral position within ±X from the hover point	± 3 ft	± 6 ft
Maintain altitude within ± X	± 3 ft	± 6 ft
Stabilize the final rotorcraft heading at the 90° point and 270° point within ±X	± 5 deg	± 10 deg
Complete maneuver within X	≤ 50 s	≤ 60 s
PIO tendencies in the capture and hold	No undesirable motions that impact task performance	No PIO (out-of-phase oscillations)

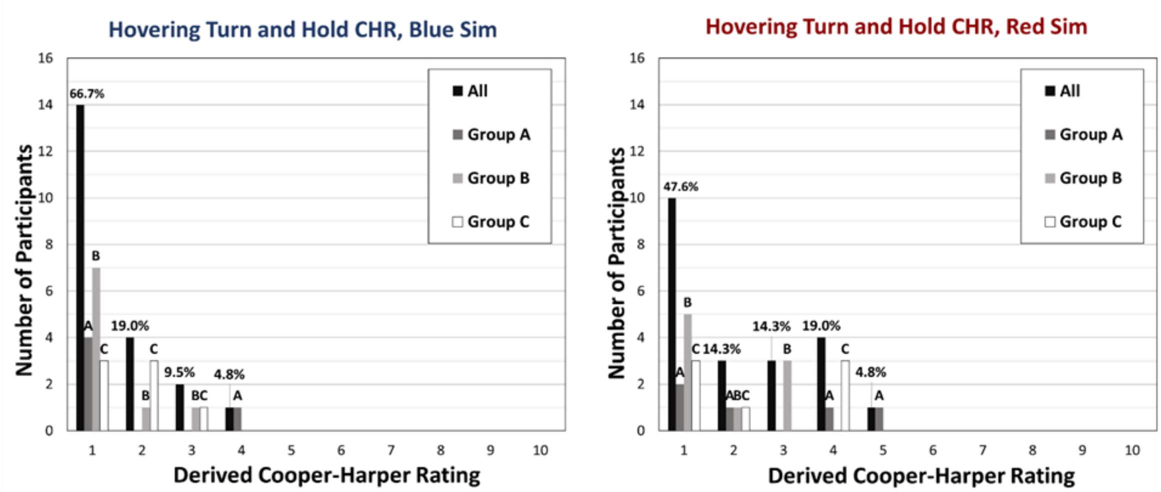

Figure 19. Hovering turn and hold Cooper-Harper Rating

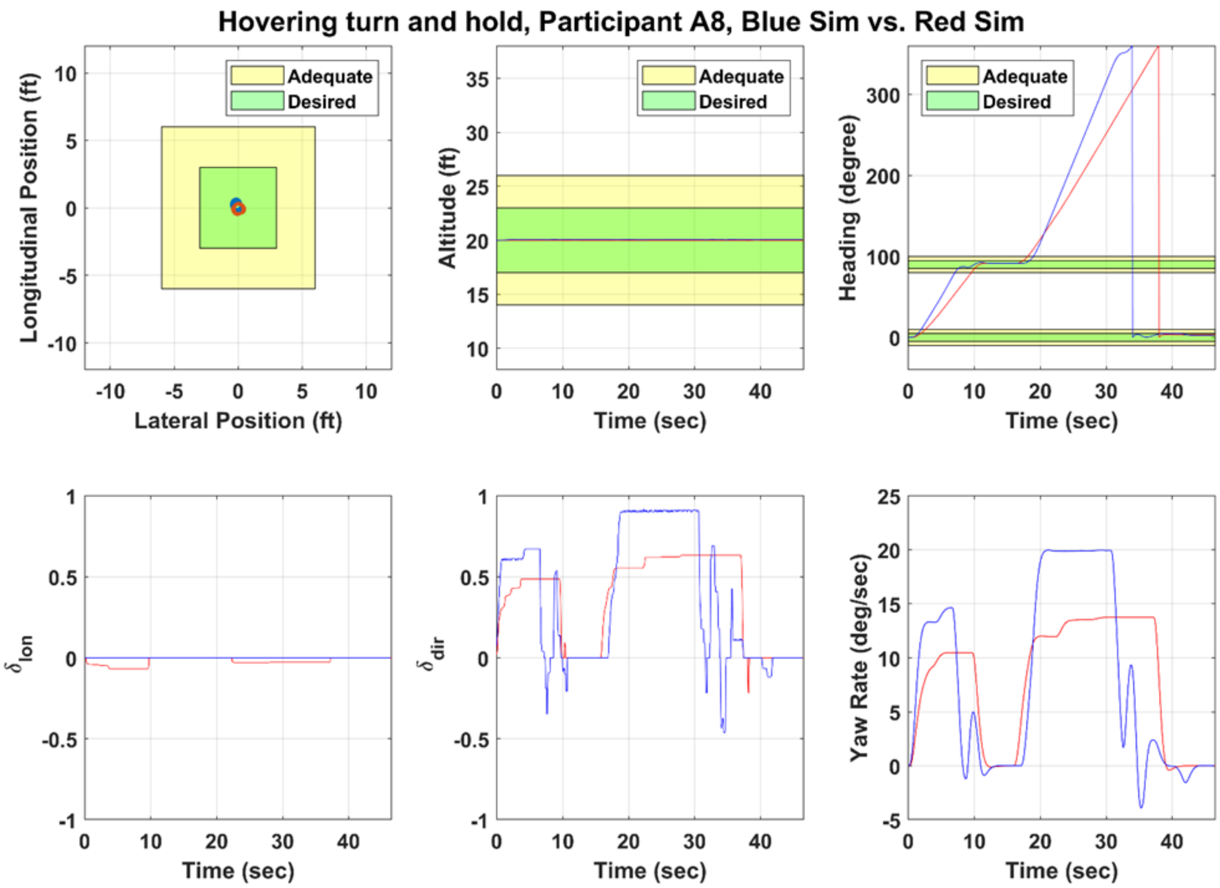

Figure 20. Hovering turn and hold, Participant A8, Blue Sim vs. Red Sim

The performance of one participant (A8) for the hovering turn and hold HQTE in Blue Sim and Red Sim is shown in Figure 20. In both cases, the position hold remains engaged throughout the maneuver, and therefore lateral and longitudinal positions remain within desired bounds at all times. The altitude hold maintains a constant altitude throughout, only briefly disengaged at the start in Red Sim by a slight vertical axis input (δ_{lon}, LHI up/down) that is cross-coupled with the pilot's intended directional input (δ_{dir}, LHI left/right). The completion times for the maneuver were in line with the desired and adequate figures (as seen in Table 11), even though the participant was not given any completion time targets. The participant's directional input δ_{dir} shows that they applied nearly full input in Blue Sim, but only around 60% input for Red Sim, resulting in a higher yaw rate and a shorter completion time in Blue Sim. The altitude, heading of the aircraft at a stabilized hover, and lateral and longitudinal position performances were within the desired requirements for all participants.

5.3 Lateral reposition and hold

Starting from a stabilized hover, this HQTE requires a lateral acceleration to a desired speed followed by deceleration to reposition the aircraft at a 400 ft lateral displacement. Its goal is to check roll and heave axis handling qualities during low-speed lateral maneuvering, the ability to recover from low-speed translational rates precisely, the ability to capture and hold position and height, and detect any undesirable coupling between the lateral inceptor axis and other axes. The suggested course for this task is shown in Figure 21. The performance requirements for this task are shown in Table 12.

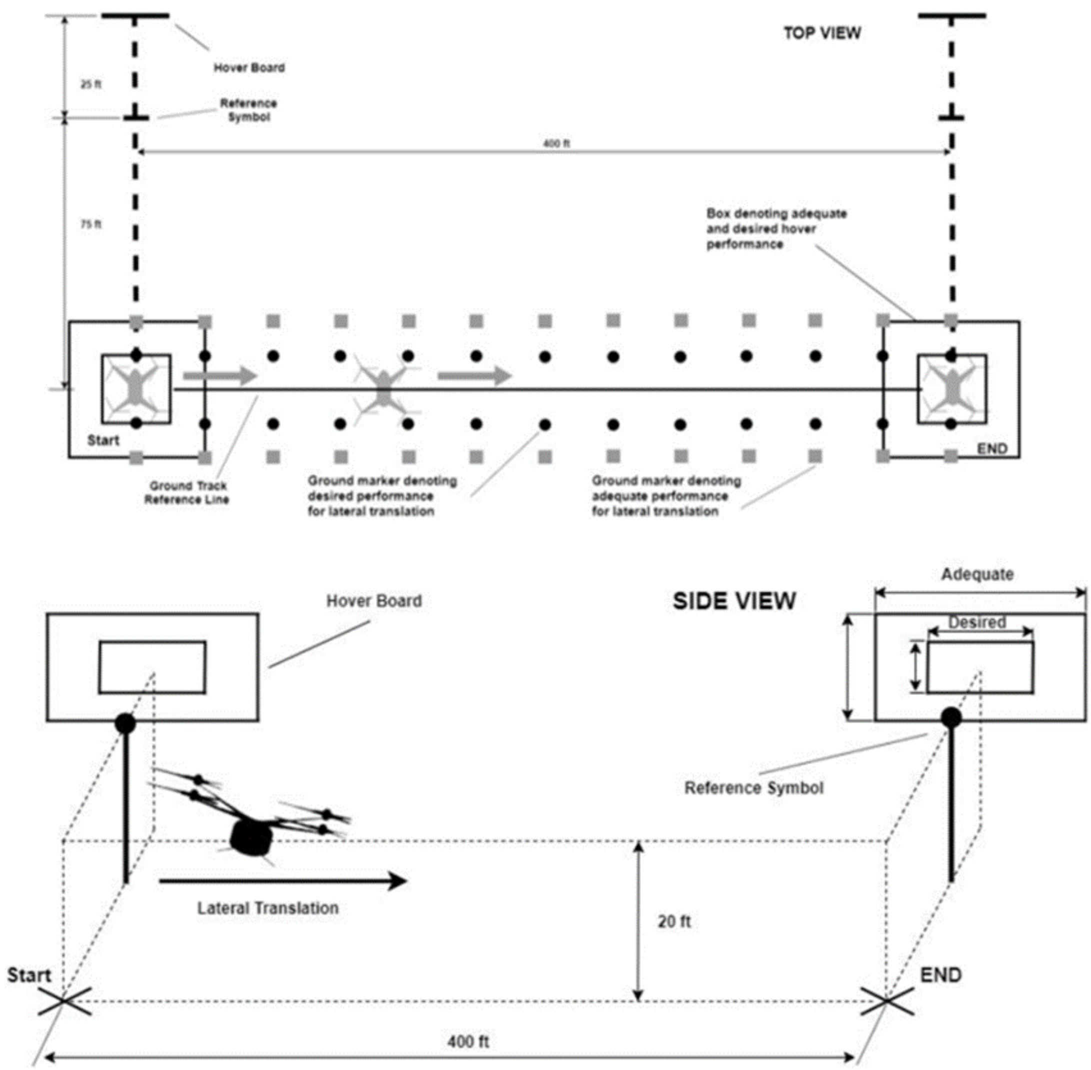

Figure 21. Suggested course for lateral reposition and hold HQTE

Table 12. Performance requirements for lateral reposition and hold HQTE

Task Performance Requirements	Desired	Adequate
Maintain ground track within ±X from the reference line	± 5 ft	± 10 ft
Attain target ground speed within ± X	± 2 knots	± 4 knots
Maintain altitude within ±X	± 5 ft	± 10 ft
Maintain heading within ±X	± 10 deg	± 20 deg
At capture, maintain ±X lat/long position	± 3 ft	± 6 ft
PIO tendencies in the capture and hold	No undesirable motions that impact task performance	No PIO (out-of-phase oscillations)

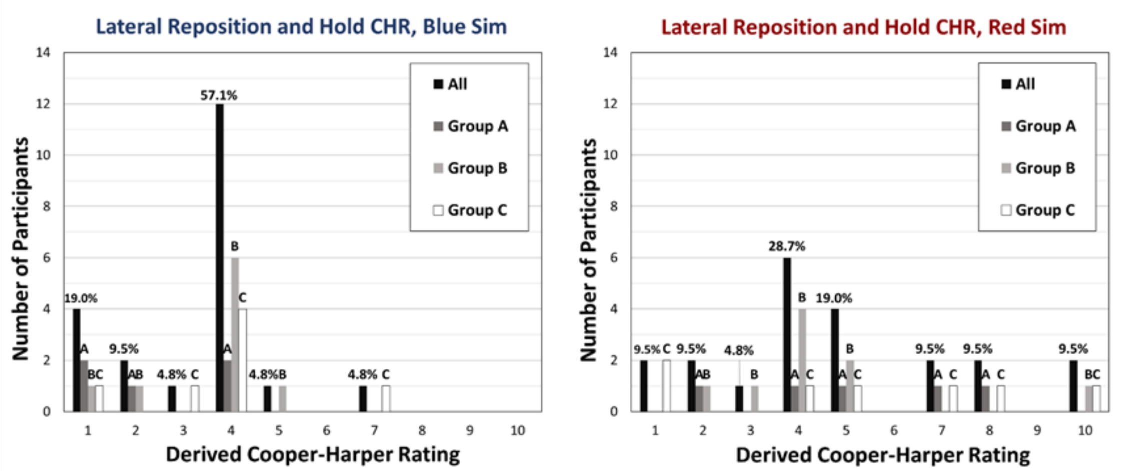

Figure 22. Lateral reposition and hold Cooper-Harper Rating

The derived CHR for the lateral reposition and hold HQTE are shown in Figure 22 and aggregate statistics are provided in Table 9. The mean CHR for this HQTE was 3.4 for Blue Sim and 4.9 for Red Sim. 33.3% of participants rated Blue Sim as Level 1 for this HQTE, compared to 23.8% for Red Sim. 61.9% of participants rated Blue Sim as Level 2, while 47.7% rated Red Sim as Level 2 for this HQTE. 28.5% of participants rated Red Sim at CHR 7 or worse (CHR ≥ 7), while only 4.8% of participants did so for Blue Sim.

The most notable observations identified based on the review of the individual participant comments for this HQTE (see Appendix C) are as follows:

- Several participants noted greater difficulty in bringing the aircraft to a stop in Red Sim. This is due to the difference in lateral inceptor (δ_{lat}) mapping between Red Sim and Blue Sim (as seen in Table 4). In Red Sim, where δ_{lat}, (RHI left/right) commands a bank angle, the pilot has to reverse their input and bank in the opposite direction in order to neutralize the lateral velocity. On the contrary, in Blue Sim, where δ_{lat} (also RHI left/right) directly commands lateral velocity in VFM, simply neutralizing the input by centering the inceptor is sufficient, as the control system manipulates the bank angle to achieve zero lateral velocity.
- For both simulators, participants noted that timing the initiation of the deceleration to return to a hover required judgment that improved with practice.
- Four participants reported undesirable coupling between lateral input (δ_{lat}, RHI left/right) and vertical axis input (δ_{lon}, RHI fore/aft) in Blue Sim. This manifested itself as a tendency to increase or decrease altitude while translating laterally.
- Five participants reported undesirable coupling between lateral input (δ_{lat}, RHI left/right) and acceleration input (δ_{acc}, RHI fore/aft) in Red Sim. This manifested itself as a tendency to move forward and backward while translating laterally.
- Two participants reported that the position hold seemed to correct against them. The research team determined that this was due to the engagement logic for the position hold system. One Group C participant reported overcoming the issue by deliberately putting in small alternating inceptor inputs that prevented the position hold logic from engaging.
- One participant (flying Red Sim) noted that not having any lateral velocity indication other than the PFD, while having to look out the side (not at the PFD), was "very frustrating".

The performance of a participant (A8) for the lateral reposition and hold HQTE in Blue Sim and Red Sim is shown in Figure 23. In both simulators, the participant attained a lateral velocity within the 10-15 knots target range that they were briefed on. The lateral control input (δ_{lat}, RHI left/right for both simulators) shows less control activity for Blue Sim than for Red Sim. In Blue Sim, δ_{lat} generates a lateral velocity command directly, which allows the pilot to hold a constant input once the desired lateral velocity has been attained. On the other hand, for Red Sim, δ_{lat} generates a bank angle command, and the pilot has to manipulate the inceptor to close the loop on the bank angle that achieves the desired lateral velocity. When decelerating to a hover in Blue Sim, the pilot simply has to neutralize (center) the lateral control input. However, in Red Sim, they have to apply the opposite inceptor input to bank away from the direction of travel to neutralize the lateral velocity. Directional input (δ_{dir}) and heading discipline were not a factor for this HQTE. The acceleration inputs (δ_{acc}, Blue Sim LHI fore/aft, Red Sim RHI fore/aft) show the pilot correcting for forward/backward drifts of the aircraft while moving laterally.

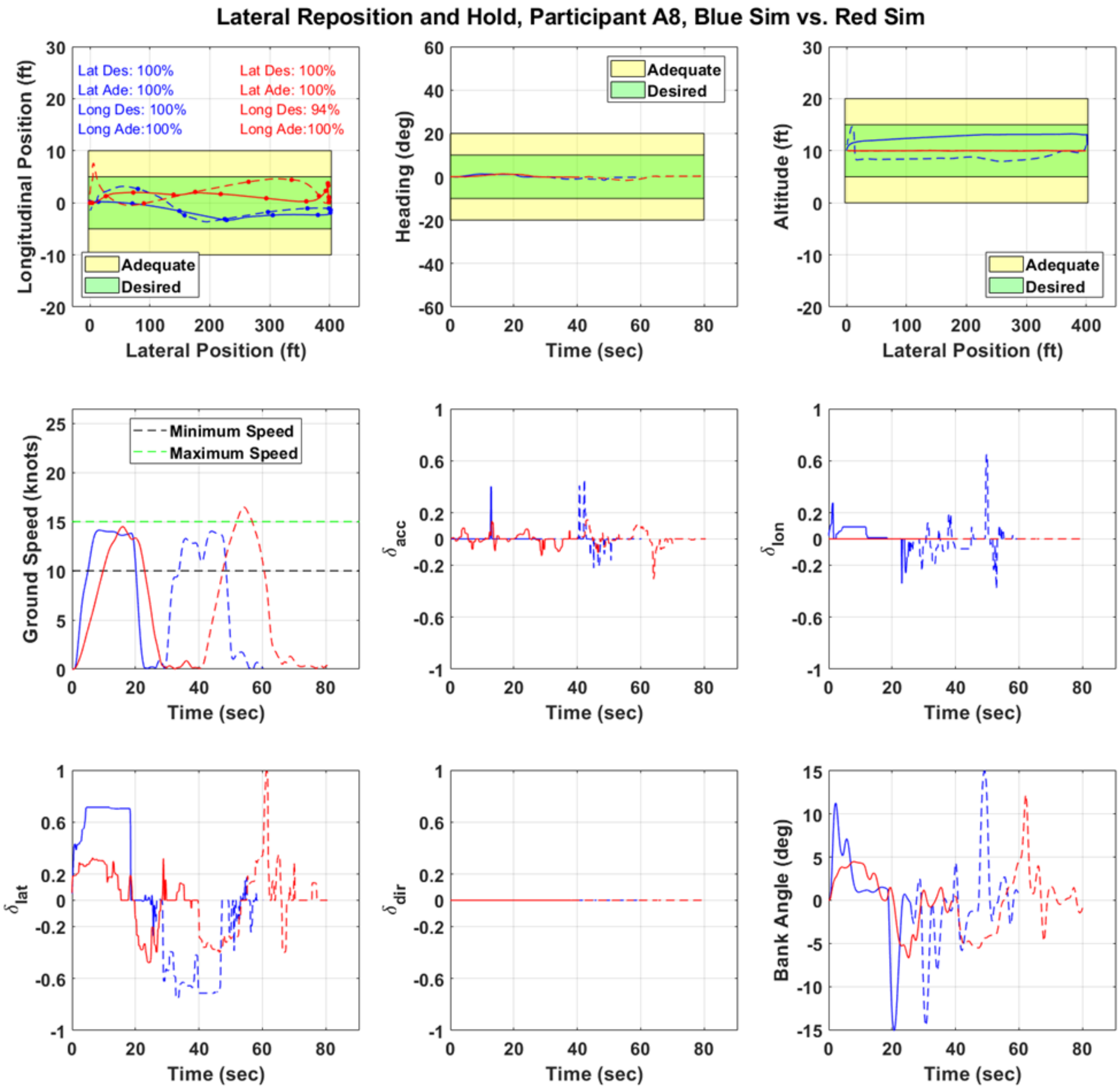

Figure 23. Lateral reposition and hold, Participant A8, Blue Sim vs. Red Sim

For Red Sim, the pilot applies no vertical axis input (δ_{lon}), LHI up/down), as a result of which the aircraft stays in altitude hold the whole time. For Blue Sim, an inadvertent vertical axis input (δ_{lon}) gets coupled with the lateral input. The nature of the coupling is such as to cause a climb while translating to the right and a descent while translating to the left. The participant remains within desired altitude bounds in both simulators. The desired position bounds are maintained for the Blue Sim case. While, for Red Sim, there is a brief excursion out of the desired band for the longitudinal position while remaining within the adequate band. The desired and adequate performances in the lateral and longitudinal directions of all participants for this HQTE are shown in Table 13.

Table 13. Desired and adequate performance for lateral reposition and hold (all participants)

Participant ID	Blue Sim				Red Sim			
	Performance Lateral (%)		Performance Longitudinal (%)		Performance Lateral (%)		Performance Longitudinal (%)	
	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate
A4	96	97	71	100	100	100	81	94
A5	92	96	100	100	98	100	72	100
A6	93	100	97	100	97	98	86	89
A7	100	100	100	100	87	89	66	91
A8	100	100	100	100	100	100	94	100
B1	92	98	89	100	92	95	60	87
B3	100	100	68	100	100	100	60	84
B4	100	100	100	100	100	100	33	41
B5	100	100	90	100	100	100	88	97
B6	100	100	85	100	100	100	93	100
B7	99	100	94	100	99	100	39	77
B8	89	99	60	100	88	93	76	90
B9	85	94	56	100	100	100	91	100
B10	92	96	100	100	98	100	94	100
C1	97	100	100	100	98	100	100	100
C4	97	99	57	100	92	94	70	85
C5	93	99	14	77	68	75	12	35
C6	92	100	50	100	89	94	70	72
C7	78	81	19	63	100	100	54	88
C8	97	100	100	100	97	97	70	91
C10	85	98	93	100	100	100	100	100

5.4 Pirouette

Starting from a stabilized hover over a point on the circumference of a 100 ft radius circle, the aircraft must be translated laterally over the circumference while keeping the nose pointed at a target object at the center of the circle. The objectives are to demonstrate precise control at low speed during multi-axis maneuvers and check for undesirable coupling between control axes and any PIO tendencies. The suggested course for the pirouette HQTE is shown in Figure 24. The required adequate and desired performances for this task are listed in Table 14.

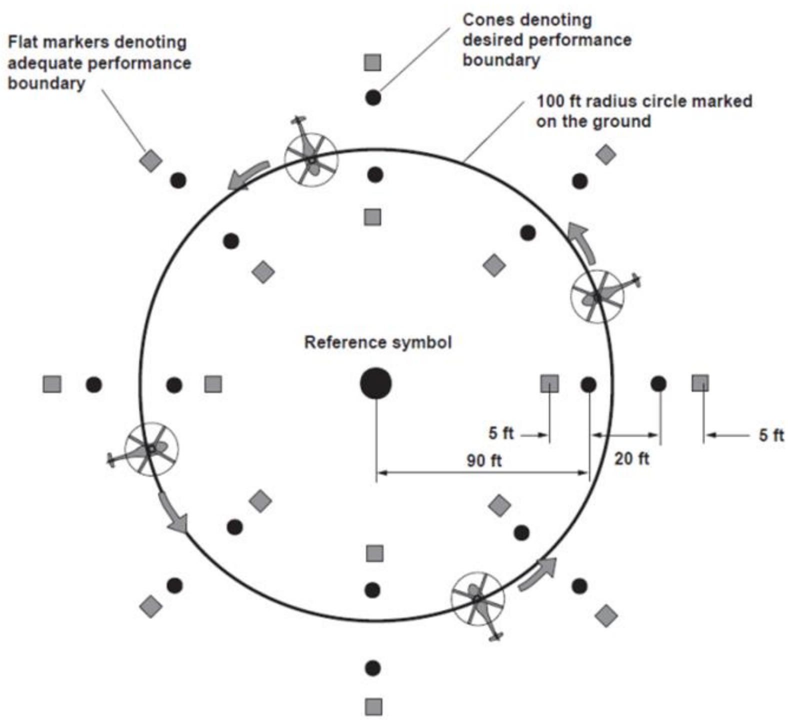

Figure 24. Suggested course for pirouette HQTE

Table 14. Performance requirements for pirouette HQTE

Task Performance Requirements	**Desired**	**Adequate**
Maintain a selected reference point on the aircraft within ±X ft of the circumference of the circle	± 10 ft	± 15 ft
Maintain altitude within ±X	± 2 ft	± 4 ft
Maintain heading so that the nose of the aircraft points at the center of the circle within ±X deg	± 5 deg	±15 deg
Complete first 180° of circle within	≤ 45 secs (4 kts)	≤ 60 secs (2 kts)
Complete second 180° of circle within	≤ 30 secs (6 kts)	≤ 45 secs (4 kts)
Achieve a stabilized hover (within desired hover reference point) within X seconds after returning to the starting point	5 secs	10 secs
Maintain the stabilized hover for an additional X sec	5 secs	5 secs

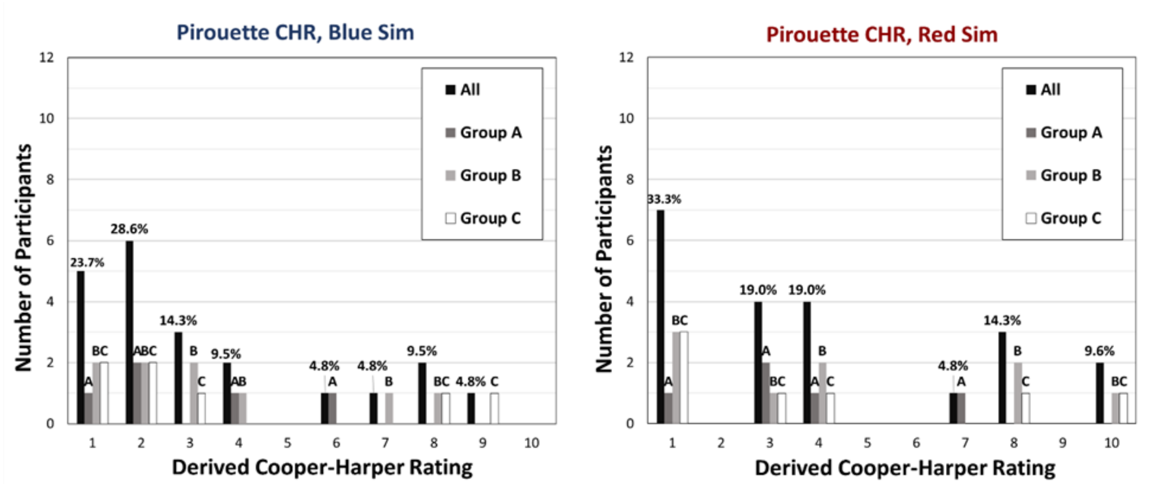

Figure 25. Pirouette HQTE Cooper-Harper ratings

The derived CHR for the pirouette HQTE are shown in Figure 25 and aggregate statistics are provided in Table 9. The mean CHR based on participant responses across all groups was 3.4 for Blue Sim and 4.1 for Red Sim. 66.6% of participants rated this HQTE as Level 1 in Blue Sim, and 52.3% in Red Sim. Conversely, 19.1% of participants gave Level 3 ratings to both Blue Sim and Red Sim for this HQTE.

Based on the review of the individual participant comments for this HQTE (as seen in Appendix C), the following observations were identified as the most notable:

- One Group A participant reported a habitual tendency to pull aft on the RHI to control altitude as this is what they were accustomed to in fixed-wing flying, even though they were in Red Sim, where fore/aft RHI movements commanded longitudinal acceleration.
- For Red Sim, two participants reported inadvertently perturbing their altitude through up/down movements of the Red Sim LHI while attempting to control yaw through left/right movements of the inceptor. One of them further noted that turning to the right (which required moving the LHI towards the body) was more difficult and resulted in a tendency to climb (upward movement of the LHI).
- One participant, flying Blue Sim, noted that the twist-top and the lateral axis movements required to perform the pirouette are in the opposite direction (e.g., moving RHI rightward to move right laterally, while twisting left to yaw to the left), creating the need to “think harder” about what control inputs needed to be applied. Another participant felt that twisting and holding the twist-top for longer periods of time could cause discomfort.
- One participant, flying Red Sim, felt that pirouetting while moving laterally to the left was easier as the RHI and LHI both needed to be deflected inward towards the participant's body. Another made the same observation, minus the reasoning.
- One participant flying Blue Sim found it more challenging to pirouette while moving left (yawing right), as this was more conducive to inadvertent fore/aft inputs to the RHI.
- One participant noted that it took a few attempts to get accustomed to tilting the Blue Sim RHI laterally while twisting its top. Another noted successfully settling upon a lateral-to-twist input ratio, at least briefly. This participant noted that an automatic altitude hold would have been beneficial. Such a hold was, in fact, present, but may have been deactivated due to the participant's inadvertent fore/aft RHI inputs.
- Participants reported difficulties in maintaining the target lateral speed of 4 or 6 knots. There were also varied comments from participants about the control sensitivities along each axis.
- One participant flying Blue Sim believed that the task would have been easier if the pilot could put in a lateral input to achieve the desired bank angle, which would then be held after neutralizing the input. This would have corresponded to a rate command attitude hold (RCAH) response type in the roll axis, whereas Blue Sim employed a lateral velocity command response type.

The performance of one participant (B3) for the pirouette HQTE in Blue Sim and Red Sim is shown in Figure 26. In this case, the participant translates laterally to the left while yawing to the right. The aircraft ground track stays within the desired band throughout the maneuver for both Blue Sim and Red Sim. Interestingly, this participant did better at achieving and maintaining the target speed (4 knots for the first half of the circle, 6 knots thereafter) in Red Sim (direct bank angle command) than in Blue Sim (direct lateral velocity command). Their strategy seems to have been to put in δ_{lat} inputs to generate bank angles that resulted in lateral velocities slightly above the target. The participant then centered the inceptor until the lateral velocity decayed to the speed target, and then repeated the process.

While translating laterally, the participant was instructed to keep the nose of the aircraft pointed toward an object located at the center of the circle. The bearing error in Figure 26 shows the heading deviation from this target. In both simulators, its time history remains within the desired band for most of the maneuver, with brief excursions into the adequate region. For the Blue Sim run, inadvertent coupling of an undesired vertical axis input (δ_{lon}, RHI fore/aft) with the lateral input (δ_{lat}, RHI left/right) resulted in altitude loss towards the end of the pirouette. This caused an excursion from the desired altitude band to the adequate band. For the Red Sim run, there is very minor coupling between the directional input (δ_{dir}, LHI left/right) and the vertical axis input (δ_{lon}, LHI up/down). As a result, the altitude hold is engaged throughout the maneuver, and the target altitude is held. The performances of all the participants in the adequate and desired ranges of position and bearing angles are shown in Table 15.

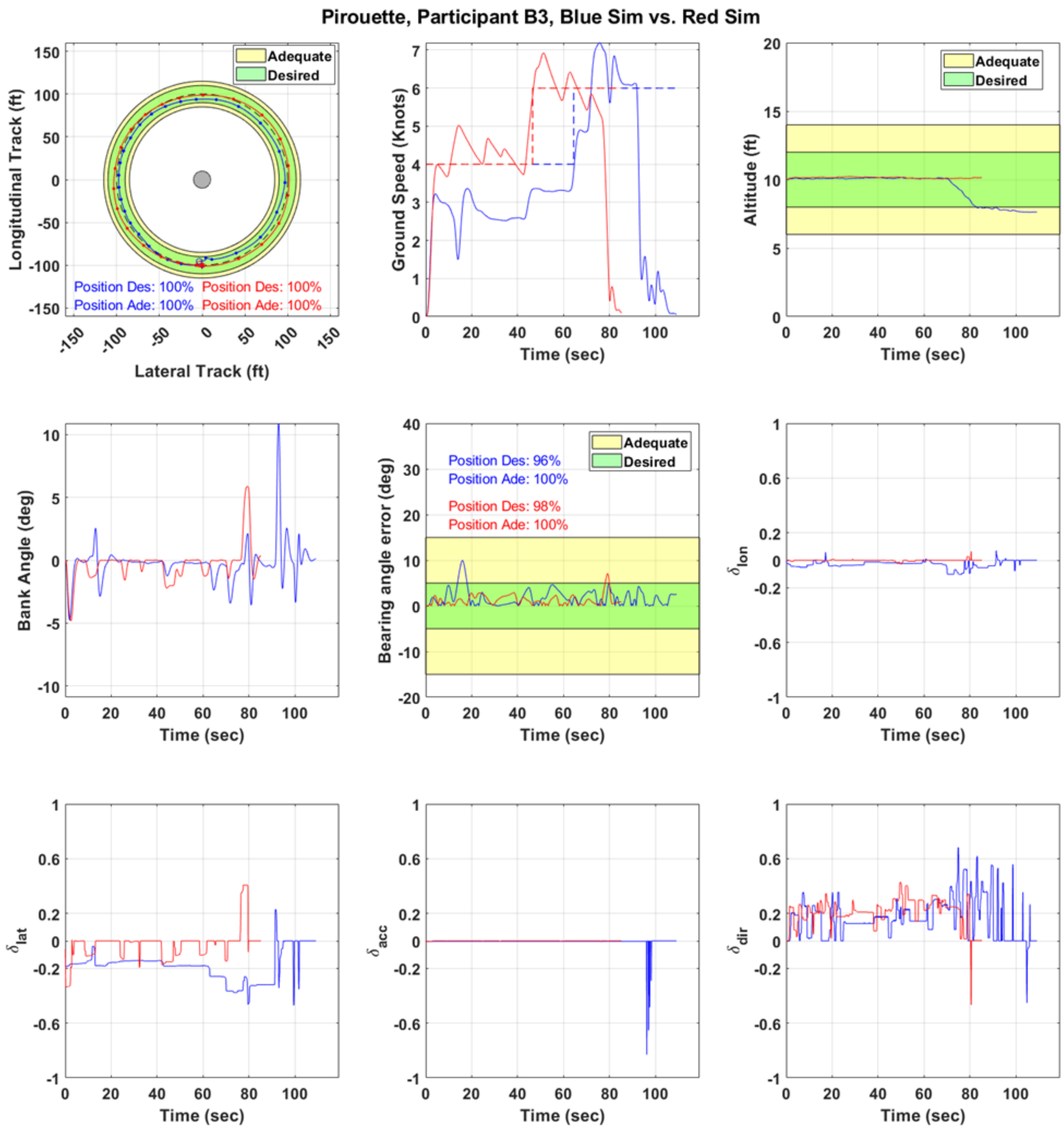

Figure 26. Pirouette, Participant B3, Blue Sim vs. Red Sim

Table 15. Desired and adequate performance for pirouette (all participants)

Participant ID	Blue Sim				Red Sim			
	Position Performance (%)		Bearing Angle Performance (%)		Position Performance (%)		Bearing Angle Performance (%)	
	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate
A4	100	100	61	100	94	100	85	100
A5	95	100	52	92	92	98	67	97
A6	100	100	62	96	49	85	76	96
A7	80	96	60	97	42	59	54	80
A8	100	100	65	100	100	100	96	100
B1	72	90	54	90	80	98	66	100
B3	100	100	96	100	100	100	98	100
B4	100	100	62	100	100	100	100	100
B5	93	100	43	89	98	100	85	100
B6	100	100	44	75	100	100	73	100
B7	100	100	53	100	100	100	57	95
B8	100	100	69	97	84	91	61	92
B9	100	100	95	100	76	100	90	100
B10	86	100	58	97	93	100	68	100
C1	53	89	59	100	100	100	83	100
C4	100	100	51	93	95	100	83	100
C5	55	68	19	59	71	78	57	100
C6	80	97	57	96	100	100	82	100
C7	100	100	73	100	100	100	83	100
C8	96	100	80	100	100	100	86	100
C10	94	100	91	100	64	90	83	100

5.5 Precision hover

This involves approaching a target hover point at a low speed while maintaining a 45° heading offset to the target ground track, and then smoothly decelerating to and maintaining a hover above the target. The goals include checking for the ability to attain a stabilized hover with precision, maintain precise position, heading, and altitude, inceptor control harmony in all axes, any PIO tendencies, and overall pilot workload. The suggested course for this HQTE is shown in Figure 27. The desired and adequate performance requirements for precision hover are listed in Table 16.

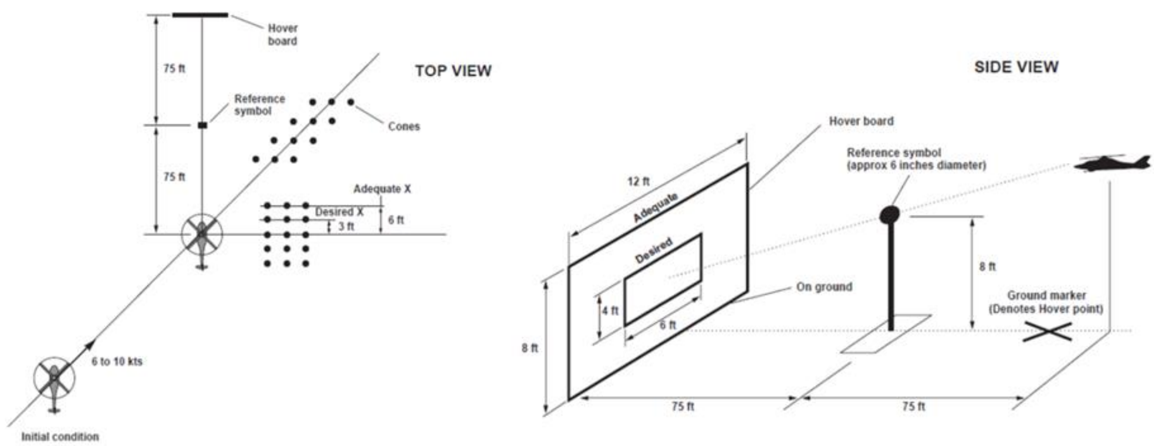

Figure 27. Suggested course for precision hover HQTE

Table 16. Performance requirements for precision hover HQTE

Task Performance Requirements	**Desired**	**Adequate**
Capture and track 45° transition within	± 3 ft	± 6 ft
Attain a stabilized hover position from start of deceleration within	8 secs	12 secs
Maintain lateral-longitudinal position	± 3 ft	± 6 ft
Maintain altitude within ±X	± 2 ft	± 4 ft
Maintain heading within ±X	± 5 deg	± 10 deg
Maintain a stabilized hover for at least X seconds	30 secs	30 secs

The derived CHR for the precision hover HQTE are shown in Figure 28 and aggregate statistics are provided in Table 9. The mean CHR across all groups was 3.2 for Blue Sim and 3.4 for Red Sim. The Level 1 – 2 – 3 rating breakdown was 61.8% – 23.8% – 14.4% for Blue Sim and 42.8% – 47.6% – 9.6% for Red Sim.

The most notable observations identified based on the review of the individual participant comments for this HQTE (see Appendix C) are as follows:

- In general, participants felt that this HQTE was more difficult than the preceding ones, requiring constant inputs on both inceptors, and felt that more practice was required to judge when the begin the deceleration to a hover.

- At least one participant noted an undesirable coupling of a vertical axis input (δ_{lon}, RHI fore/aft) with their intended lateral input (δ_{lat}, RHI left/right) in Blue Sim, which caused a change in altitude.
- For Red Sim, five participants noted an increase in the required control effort to neutralize the lateral velocity. Since their lateral control input ($\delta_{lat,}$ RHI left/right) commanded bank angle and not lateral velocity, they had to manipulate bank angle to neutralize the lateral velocity themselves.
- The previously described deficiency of the position hold system that interfered with the pilot's attempts to do precise maneuvering was noted again for this HQTE.
- Given the required 45° track, one participant attempted to move the Red Sim RHI forward-and-right at a 45° angle but found that the lateral acceleration exceeded the forward acceleration (this is because of different mappings along these two axes, see Table 4). Other participants noted that having both fore-aft and lateral motions controlled using the RHI was an advantage for Red Sim for this HQTE.

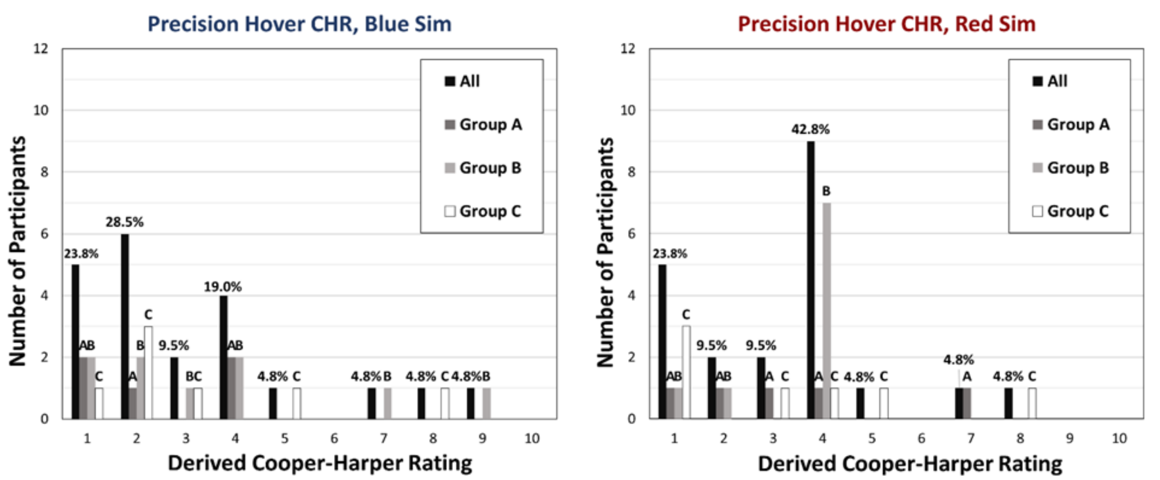

Figure 28. Precision hover HQTE Cooper-Harper ratings

The performance of a participant (A7) on the precision hover HQTE on Blue Sim and Red Sim is shown in Figure 29. A note regarding the setup for this HQTE in Blue Sim is in order. The precision hover HQTE requires the pilot to look and track to the right at a 45° angle, where an "A-pillar" that is part of the Blue Sim cockpit frame limits visibility. Therefore, the aircraft starting position for Blue Sim was moved forward approximately 14.5 feet to allow the pilot a clear view of the 45° path to be tracked as well as the target hover box while looking at the side screen. This is seen in the offset starting position for Blue Sim in Figure 29 and the generally "ahead-of-the-line" trajectory until reaching the vicinity of the hover boards, where the pilot switches to using the latter for alignment. This offset was accounted for in the calculation of the percentage of time spent in desired and adequate zones. In both simulators, the participant achieved the target 6-10 knot speed range while crabbing to the right. While attempting to decelerate to a hover while aligning with the hover boards in Red Sim, the participant overshot the box. The overshoot was much smaller for Blue Sim. This is due to the difference in the lateral axis mapping (bank command in Red Sim versus lateral velocity command in Blue Sim). The position performance of all participants is summarized in Table 17.

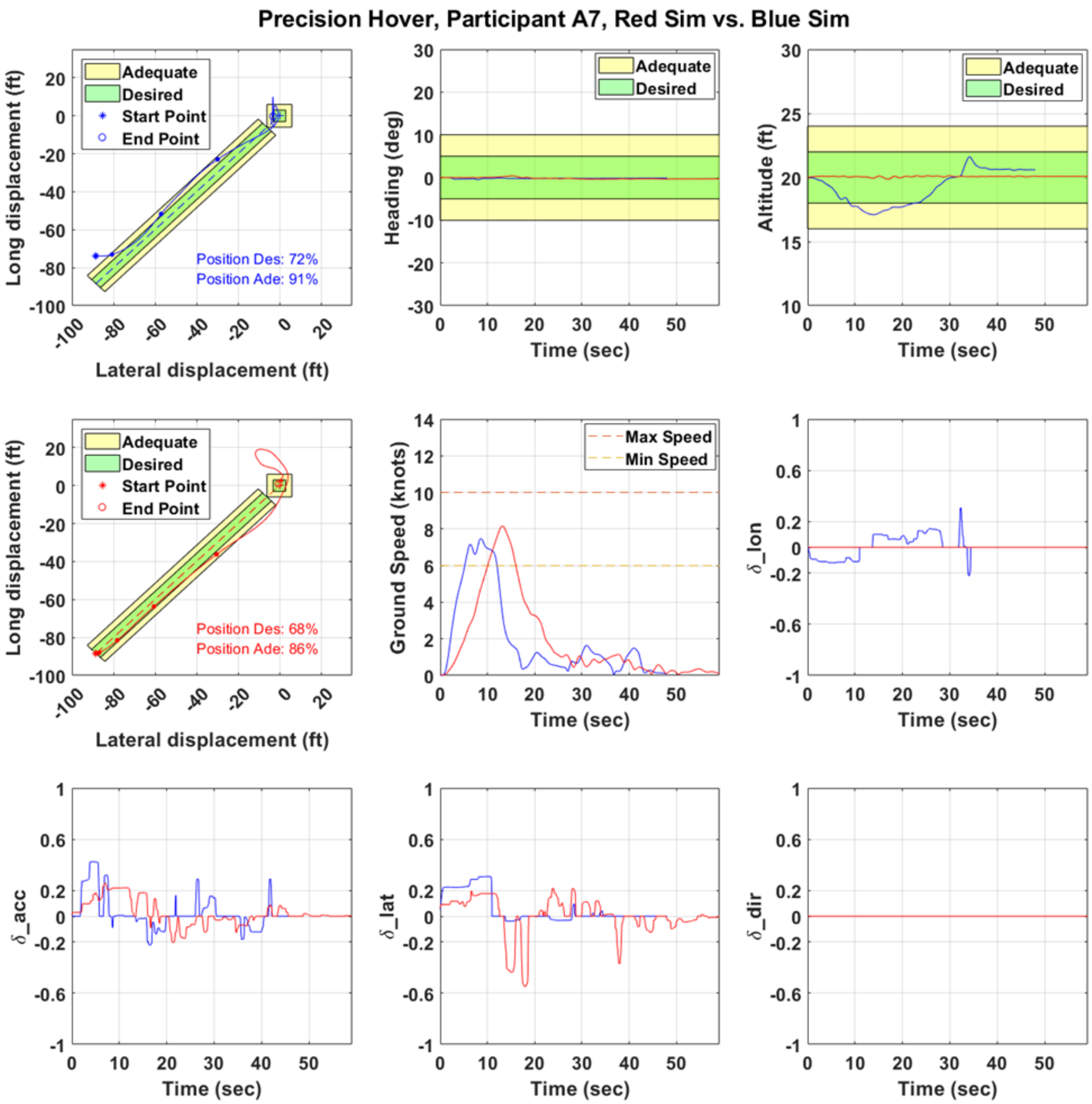

Figure 29. Precision hover, Participant A7, Blue Sim vs. Red Sim

Table 17. Desired and adequate performance for precision hover (all participants)

Participant ID	Blue Sim		Red Sim	
	Performance Position (%)		Performance Position (%)	
	Desired	Adequate	Desired	Adequate
A4	62	77	31	57
A5	59	76	56	74
A6	38	70	56	83
A7	72	91	68	86
A8	48	84	82	100
B1	39	58	28	39
B3	79	93	47	59
B4	71	95	45	54
B5	52	81	64	82
B6	45	58	66	97
B7	37	82	44	72
B8	56	74	59	79
B9	38	69	66	81
B10	33	61	76	100
C1	67	83	100	100
C4	51	69	91	100
C5	42	55	35	47
C6	36	56	71	100
C7	56	70	42	51
C8	51	66	43	81
C10	43	76	74	100

5.6 UAM mission simulation

The representative UAM mission that was simulated is shown in Figure 30. From takeoff to landing, the pilot is provided navigation and speed cues on the PFD as well as overall situational awareness of the flight plan through a moving map displayed using the Garmin Pilot™ application. Starting from a hover a few feet above the takeoff/landing pad, the pilot departs southbound and commences the VFM-to-FFM transition on a 6° climbing flightpath to clear an obstacle. Thereafter, the pilot navigates the en-route waypoints, which takes the aircraft on an anti-clockwise circuit in the San Francisco Bay area. The landing approach is made flying northbound, clearing the same obstacle before commencing a continuously decelerating descent to the takeoff/landing pad along a 6° glideslope. The CHR for the takeoff and VFM-FFM transition are shown in Figure 31. The mean rating was 2.6 for Blue Sim and 2.0 for Red Sim. The breakdown of Level 1 – 2 – 3 ratings was 71.4% − 28.6% − 0% for Blue Sim and 90% − 10% − 0% for Red Sim.

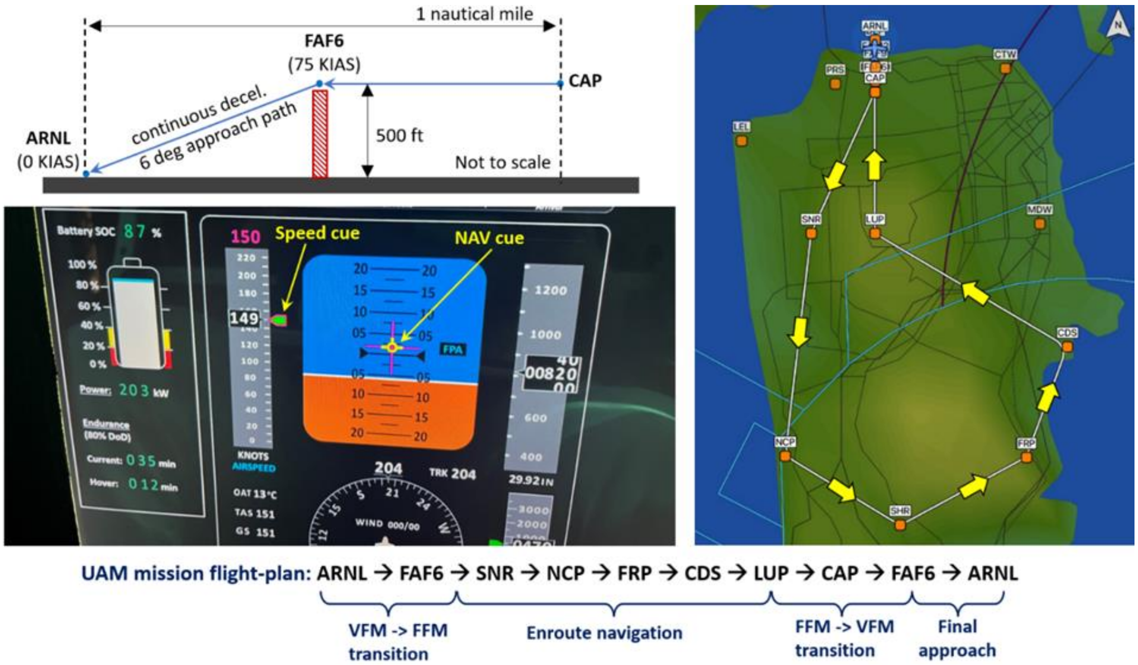

Figure 30. UAM mission profile

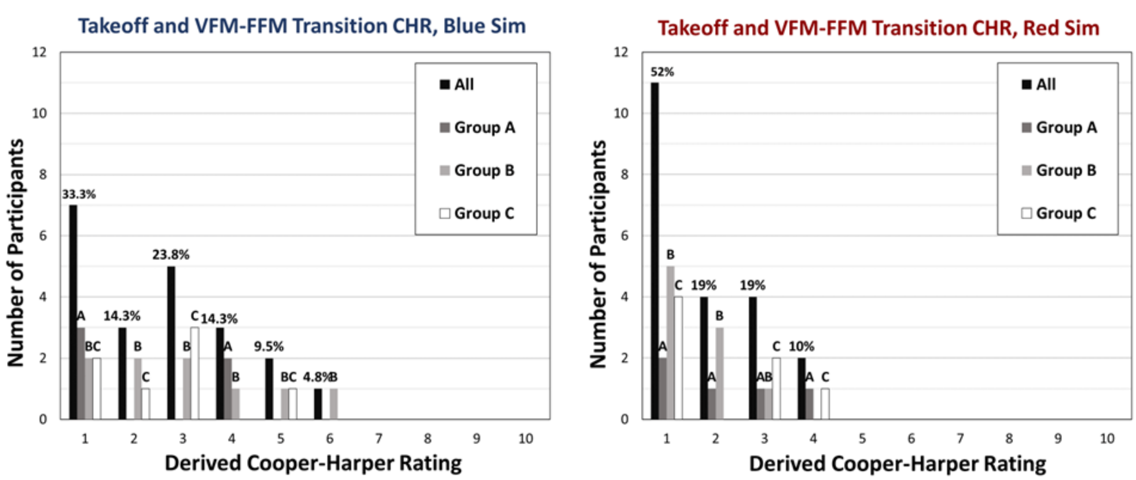

Figure 31. Takeoff and VFM-FFM transition Cooper-Harper ratings

There is a possibility that participants preferred the absence of any mode blend for vertical path control in Red Sim to the blend present in Blue Sim between height rate command and flightpath angle rate command, flightpath angle hold. This blend occurs as the lift propulsors shut down and the aircraft transitions to fully wing-borne flight but is not currently associated with any aural indications.

The most notable observations identified based on the review of the individual participant comments for this HQTE (see Appendix C) are as follows:

- The general comments regarding transition from VFM to FFM were positive and participants felt that the control of the aircraft was intuitive.
- One astute participant observed that the (TECS) oscillated several times between speed priority and path priority modes, as indicated on the PFD. The reasons for this have been identified by the research team and will be rectified.
- Several participants recommended additional advisories or alerts appearing on the cockpit displays during the transition.
- Some participants commented on pitch transients that they experienced during the transition.

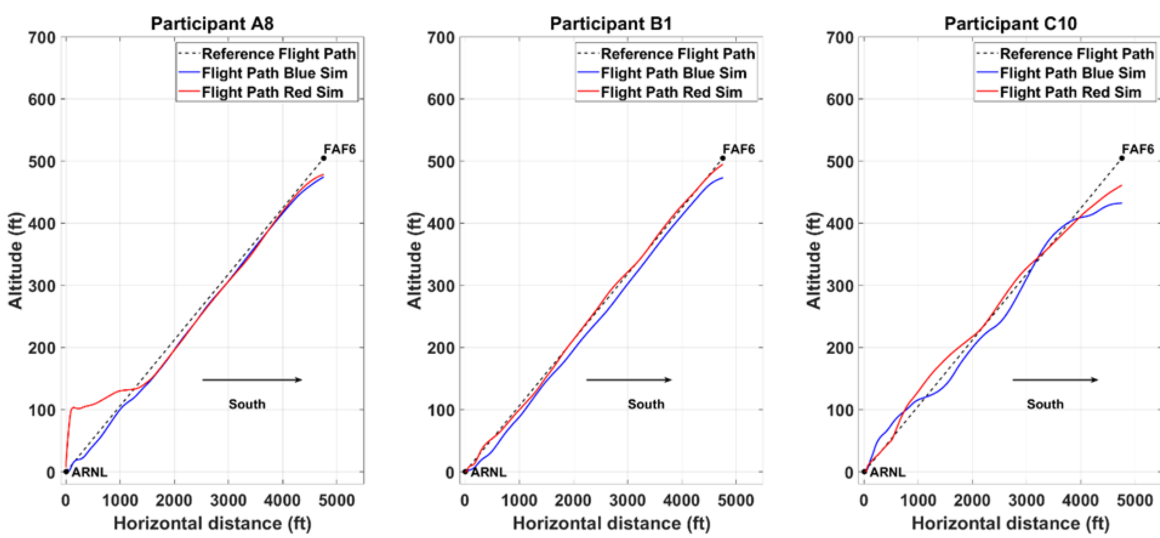

Figure 32. Initial part of VFM to FFM transition in UAM mission simulation

The initial part of the VFM-FFM transition for three participants (A8, B1, and C10) is shown in Figure 32. Starting from the pad (ARNL), the participants were cued by the flight director (see Figure 30) to transition along a 6° flightpath towards waypoint FAF6.

Participants A8 and B1, with flight experience (thus, tracking experience) established both Blue Sim and Red Sim on the desired flightpath. A8, while flying Red Sim, initially climbed almost vertically (for unknown reasons), but thereafter, intercepted the desired flightpath from above. Participant C10, with no flight experience, still managed to track the desired departure path in both Blue Sim and Red Sim, albeit not as precisely. The gentle rounding off of trajectories near FAF6 is due to the flight director advancing to the next waypoint in the mission.

The performance of a Group A, Group B, and Group C participant (A8, B9, and C7) for the en-route navigation portion of the UAM mission profile is shown in Figure 33. The objective is to manipulate the inceptors to place the flightpath marker on top of the guidance cue (as seen in Figure 30). Both these PFD elements can move up/down and left/right. As seen in Figure 33, all three participants tracked the en-route waypoints. For lateral navigation, the participants in Red Sim directly commanded bank angle through δ_{lat} (RHI left/right in both simulators). Therefore, to execute a turn, they had to maintain a lateral inceptor input throughout the turn. Returning to wings-level flight simply required neutralizing the lateral input. In Blue Sim, where δ_{lat} generated a roll rate command with bank angle hold, participants could establish a bank angle and then center the inceptor. However, they were then also responsible for rolling to wings-level. As can be seen from Figure 33, the difference in lateral inceptor mapping had a noticeable effect on lateral path tracking for two of the three participants. It should be noted that participants did not receive prior training regarding tracking flight director cues. Unfortunately, the debriefing questionnaire did not capture whether or not the participants referred to the Garmin Pilot™ map while flying the mission, which would have allowed them to anticipate an upcoming turn.

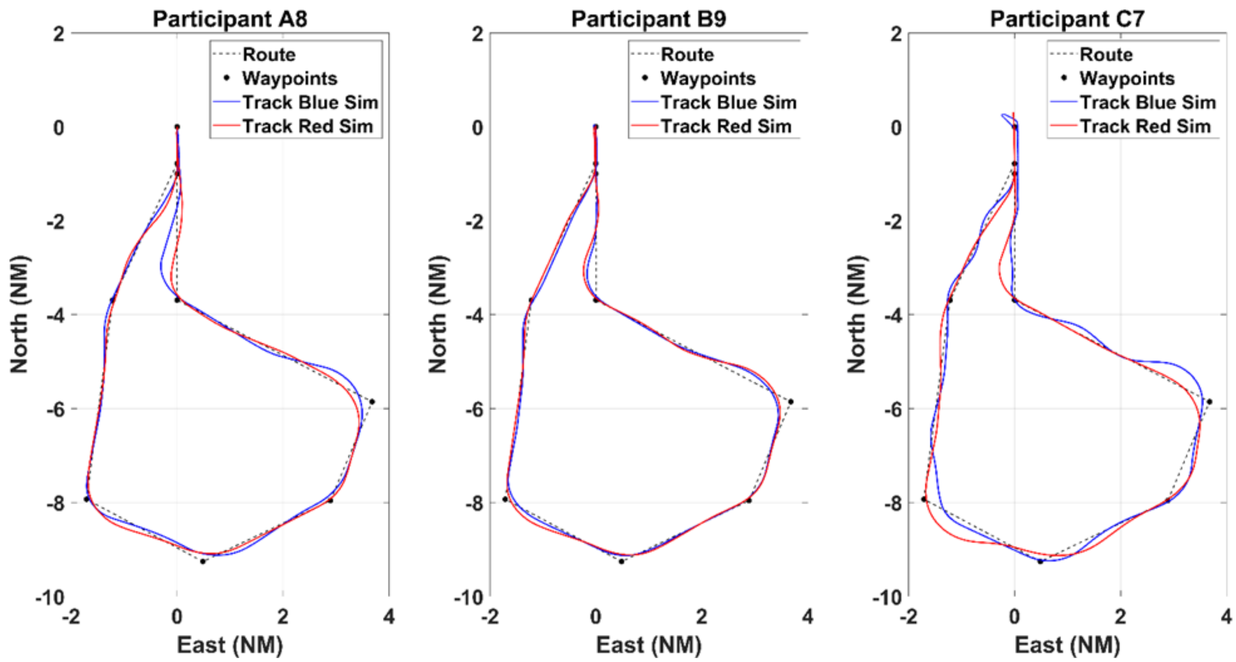

Figure 33. En-route navigation for UAM mission simulation

The CHR for the FFM-VFM transition and landing are shown in Figure 34 and aggregate statistics are provided in Table 9. The average CHR across all groups was 4.3 for Blue Sim and 4.6 for Red Sim. The breakdown of Level 1 – 2 – 3 ratings was 61.9% – 23.8% – 9.5% for Blue Sim and 52.3% – 19.0% – 14.3% for Red Sim.

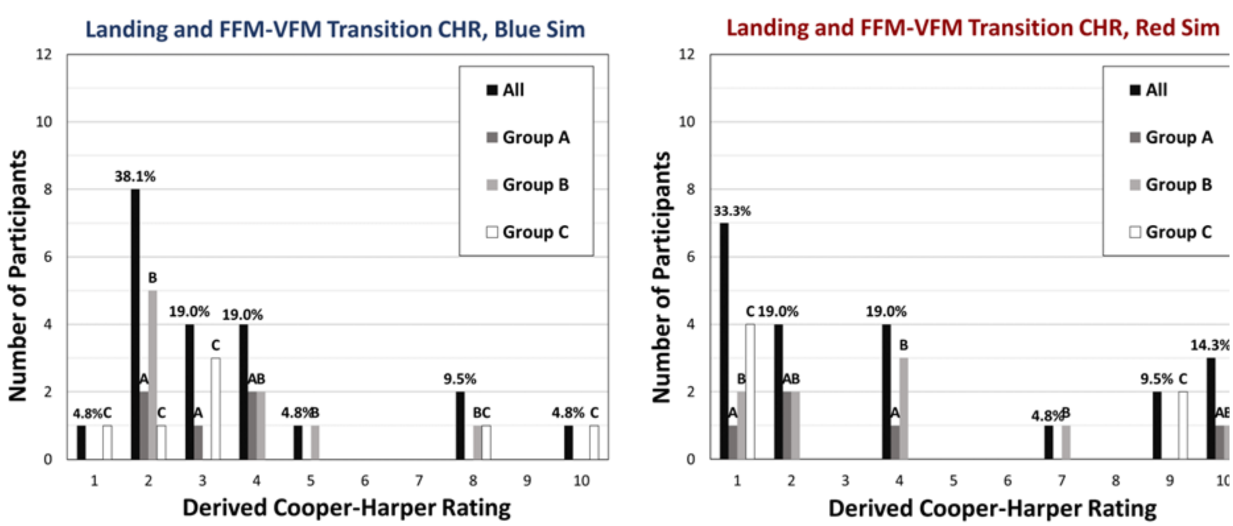

Figure 34. FFM-VFM transition and landing Cooper-Harper ratings

The most notable observations, identified based on a review of individual participant comments (see Appendix C) are:

- Several participants noted difficulty in simultaneously decelerating the aircraft while also descending. Some participants also noticed the beginnings of a pilot-induced roll oscillation if commanding lateral inputs while descending in vertical flight mode.
- For Red Sim, several participants with fixed-wing experience noted confusion regarding the control of speed via fore/aft movement of the RHI, likely as they were used to this controlling pitch/flightpath in fixed-wing aircraft.
- Several participants noted that the flight director that drove the guidance cues on the PFD was deficient when it came to guiding them to a landing. The research team had insufficient time to fine-tune the flight director gains. The gains were set up for en-route navigation and not adjusted for the more precise tracking required for a landing approach. This deficiency will be rectified for subsequent simulations.

The performance of three participants, A7, B3, and C4, during the UAM landing approach in Blue Sim and Red Sim, is shown in Figure 35. The landing approach involves a descent along a 6° glideslope starting at FAF6 and ending at ARNL. The participants received vertical and lateral guidance cues from the flight director (see Figure 30) to help them in tracking the approach path, in addition to speed cues to help them decelerate smoothly along the descent. Participants A7 and B3 (with flight experience) were able to stabilize both Blue Sim and Red Sim on the desired approach path until they got to a low altitude. It is likely that at this point, they began to visually track toward the landing pad. Despite not having pilot training or flight experience, Participant C4 was also successful in establishing the approach path and flying both Blue Sim and Red Sim down to a landing, although their tracking performance was poorer (which is to be expected).

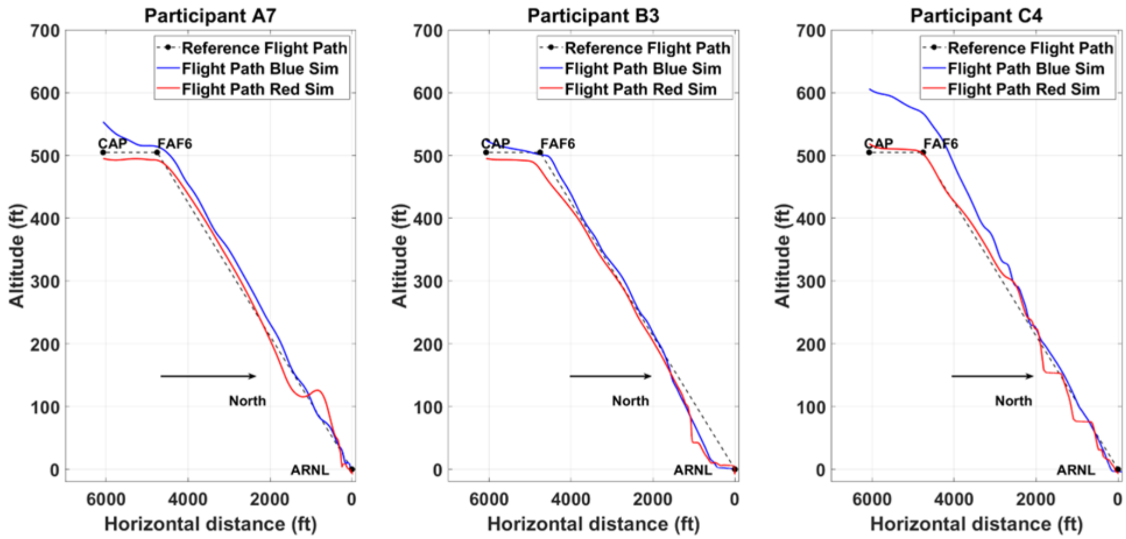

Figure 35. UAM landing approach simulation

Figure 36. VFM HQTE courses modeled and deployed in X-Plane visual environment

6 Conclusions

An SVO-centric fly-by-wire flight control system (FCS) architecture for a lift-plus-cruise (LPC) aircraft designed around the Total Energy Control System (TECS) was deployed to two VSDDL flight simulators, Blue Sim and Red Sim, with different inceptor layouts and inceptor-to-command mappings. The Blue Sim inceptor scheme was somewhat similar to that found in conventional fixed-wing aircraft, while the Red Sim inceptor scheme was somewhat similar to that found in rotorcraft. To test the developed FCS architecture, inceptor layouts, and cockpit displays, participants were recruited and categorized into three groups: Group A, comprising certified flight instructors; Group B, comprising pilots and trainee pilots; and Group C, comprising non-pilots. Piloted simulations, in which these participants were asked to fly both simulators through a series of HQTEs, demonstrated that participants in all three categories (even Group C non-pilots) were able to successfully perform the tasks with relatively little instruction, training, or practice.

Some coupling between inceptor axes was observed from analysis of the logged data and also recorded in participant feedback. The coupling occurred for different HQTEs in the two simulators. However, rather than arriving at a conclusion regarding the advantage/disadvantage of either inceptor layout, this warrants a more detailed usability analysis of the inceptor designs and layouts to determine whether the observed coupling can be reduced or eliminated through more ergonomic design and placement of the inceptors or adjustment of the inceptor resistances, combined with updates to the existing inceptor filters and dead zones.

The position hold function worked adequately for maneuvering scenarios where it was never disengaged (e.g., hovering turn). However, for maneuvering scenarios such as lateral reposition and hold and precision hover, where position hold is disengaged by control input at the start of the maneuver and re-engaged at its conclusion, some participants reported that the position hold corrected against them while they attempted fine maneuvering, or engaged prematurely. The research team has determined that this deficiency pertains to the engagement logic for the position hold, which will be refined for subsequent work.

Similar refinements will be pursued for the flight director, for which participant feedback identified some deficiencies and limitations. Most of these have to do with the selection of gains for the flight director, and the adjustment of these gains depending upon the phase of flight (en-route or terminal).

The Group A and Group B participants in this study only had fixed-wing aircraft experience. No participants had rotorcraft, military, or airline experience. Even though five flight instructors participated, none of them had in excess of 800 PIC hours at the time of participation. Future studies will attempt to expand both the size and the demographics of the pilot participant pool to include aviators with more diverse flying backgrounds and experience levels.

With the exception of the UAM mission simulation, the remaining simulation tasks involved HQTEs that pertained to hovering flight, i.e., vertical flight mode. Since most UAM concepts transition to a wing-borne FFM, HQTEs pertaining to forward flight must also be assessed rigorously. This is an avenue for future work.

The simulations reported in this work were conducted in calm atmospheric conditions without any wind or turbulence, in good visual environment, and with a nominal vehicle state (no failures). Future work will involve piloted simulations with wind, gust, and atmospheric turbulence, in degraded visual environments, and with control effector or system failures in order to stress the pilot-vehicle system and observe the impact on pilot performance on HQTEs.

7 References

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A LPC-03 aircraft characteristics

Table A- 1. LPC-03 sizing summary (for all-electric propulsion architecture)

Parameter	**Metric Units**	**English Units**
Maximum takeoff mass (MTOM)	$1822\ kg$	$4018\ lb$
Empty mass	$978\ kg$	$2156\ lb$
Battery mass	$445\ kg$	$981\ lb$
Payload mass	$400\ kg$	$882\ lb$
Moment of inertia, roll (I_{xx})	$3859\ kg.m^2$	$91575\ lb.ft^2$
Moment of inertia, pitch (I_{yy})	$3231\ kg.m^2$	$76673\ lb.ft^2$
Moment of inertia, yaw (I_{zz})	$6586\ kg.m^2$	$156288\ lb.ft^2$
Main wing area	$7.47\ m^2$	$80.4\ ft^2$
Main wing span	$9.47\ m$	$31.1\ ft^2$
Horizontal tail area	$1.30\ m^2$	$14.0\ ft^2$
Horizontal tail span	$3.90\ m$	$12.8\ ft$
Fuselage length	$4.83\ m$	$15.8\ ft$
Lift propeller diameter	$1.54\ m$	$5.05\ ft$
Motor rated power (each)	$8\ x\ 92\ kW$	$8\ x\ 123\ hp$
Cruise propeller diameter	$1.96\ m$	$6.43\ ft$
Cruise motor rated power	$254\ kW$	$341\ hp$
Wing loading (MTOM)	$244\ kg/\ m^2$	$50\ lb/\ ft^2$
Disc loading (MTOM, hover)	$122\ kg/\ m^2$	$25\ lb/\ ft^2$
Power-to-weight ratio (MTOM, hover)	$0.28\ kW/kg$	$0.17\ hp/lb$

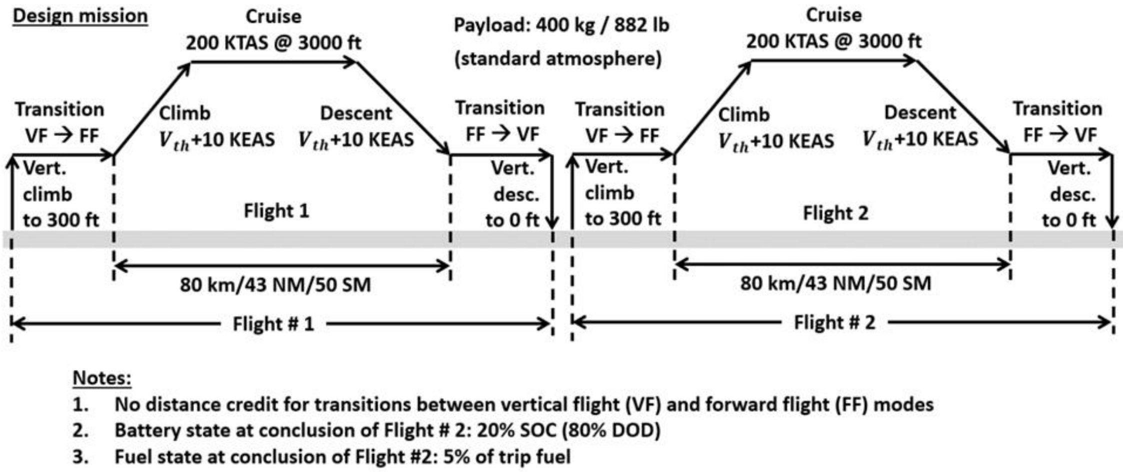

Figure A-1. UAM mission profile used to size LPC-03 configuration

B Procedure for Derived Cooper-Harper Ratings (CHR)

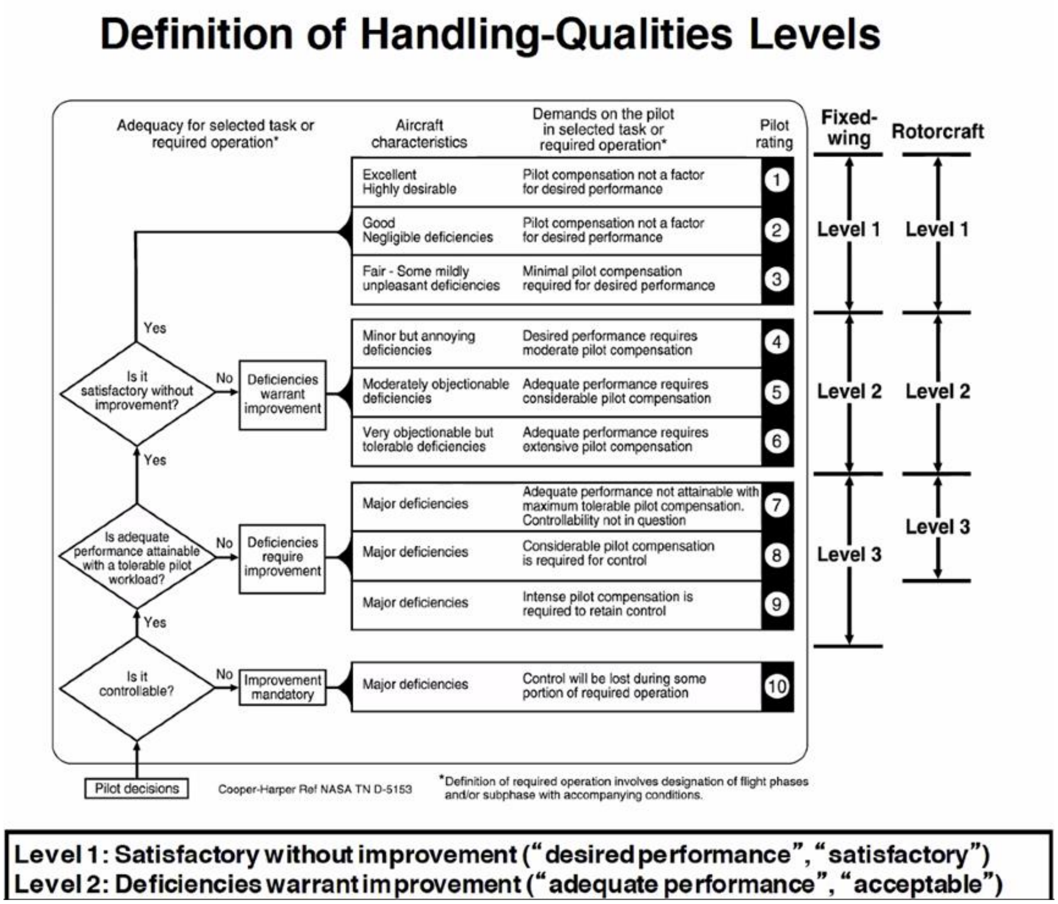

Figure B- 1. Cooper-Harper handling qualities rating scale

Task Workload Questionnaire

Q1. Did you find the aircraft to be controllable? Answer YES or NO below.

• Yes

• No (Earns CHR = 10)

If you answered "YES" to Q1, please answer the following:

Q2. Were you able to perform the task adequately with tolerable pilot workload (defined as how hard you had to work to perform the task)?

• Yes

• No. I had to work intensely in order to maintain control of the aircraft. (CHR = 9)

• No. I had to work considerably hard in order to maintain control of the aircraft. (CHR = 8)

• No. The aircraft was controllable, but my workload was still too high to perform the task adequately. (CHR = 7)

If you answered "YES" to Q2, please answer the following:

Q3. In your opinion, are the aircraft characteristics that you experienced satisfactory, without any further improvement?

• Yes

• No. There were very objectionable but tolerable deficiencies. Extensive control corrections were required to perform the task adequately. (CHR = 6)

• No. There were moderately objectionable deficiencies. Considerable control corrections were required to perform the task adequately. (CHR = 5)

• No. There were some minor but annoying deficiencies. Moderate control corrections were required to perform the task adequately. (CHR = 4)

If you answered "YES" to Q3, please answer the following:

Q4. How would you rate the aircraft flight characteristics that you experienced on this task?

• Fair. The task could be performed adequately with minimal control corrections. (CHR = 3)

• Good (CHR = 2)

• Excellent (CHR = 1)

C Derived CHR & Participant Comments

Table C- 1. Vertical reposition and hold CHR and participant comments

Participant	Blue Sim	Red Sim
A4	CHR: 4 Comments: Constant control pressures required vs a rate system used on airbus. Tried to only use pitch control on stick, yet caught roll axis in the control inputs, may want to consider changing stick. Overall though, very, very minor item, but could become problematic in high workload environment.	CHR: 3 Comments: VERY SIMPLE and easy.
A5	CHR: 1 Comments: Much more controllable compared to the red sim. Position hold feature remains elusive to figure out but overall task was very simple.	CHR: 4 Comments: The controls perform as requested but the feedback feels wrong. The sensitivity comes far too late in the travel and it makes fine work difficult. When fine tuning my alignment with the hoover boards, I had to constantly put in very jerky inputs to accomplish my task. Made worse by the location of the VSI in order to verify how much of an input I was applying.
A6	CHR: 4 Comments: The second run was fine. On the third run the aircraft seemed to trend right which made it slightly difficult to stay on target.	CHR: 1 Comments: Flight controls felt easy to manipulate. Aircraft control felt good. The position hold seemed to have less affect which was nice. This sim felt better.

Participant	Blue Sim	Red Sim
A7	CHR: 1 Comments: It is relatively easy to position the aircraft vertically, except for the minor lateral deviations that seems to be inadvertent. With practice and getting used to the right inceptor, the maneuver can be done very easily with minimal inadvertent deviations.	CHR: 4 Comments: The controls seem very sensitive. I have extensive experience in flight simulators, so I appreciate the fact that sims are significantly more sensitive than the actual aircraft. To maintain the ball within the specified point, it required minor, but relatively consistent corrections.
A8	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
B1	CHR: 3 Comments: I was trying to only go vertical, however, sometimes the controls were a bit sensitive and moved me horizontal not allowing me to center the dot as easy as I would like. However, I believe with practice this shouldn’t be a problem.	CHR: 4 Comments: The aircraft seemed a little sensitive, but I believe with little practice it would be easy to fix.
B3	CHR: 4 Comments: I would change the "throttle" or increase/decrease altitude function to the left controller, and keep the right stick or controller as pitch, bank, and yaw like in forward flight.	CHR: 1 Comments: (None)
B4	CHR: 4 Comments: Control inputs with the right-hand interceptor were very responsive. In some cases, overcorrection may	CHR: 7 Comments: Aircraft had a late response to control inputs on the 3rd try. Therefore,

Participant	Blue Sim	Red Sim
	happen, but I believe it is just a task that would require practice.	corrections had to be constantly being made to keep alignment.
B5	CHR: 3 Comments: The sensitivity of the controls in two dimensions makes it a little bit difficult to maneuver the drone; if the resistance of the controls were a little greater it would help to minimize the motion in an undesired direction.	CHR: 1 Comments: The aircraft is easy to control in the vertical axis with the control lever that is provided and intuitive which also helps in its ease to maintain control.
B6	CHR: 3 Comments: Could be a little less sensitive to control inputs but overall, it was really good!	CHR: 2 Comments: Seems to work well and be pretty easily controllable.
B7	CHR: 3 Comments: When pushed directly forward, the right yoke tends to move the aircraft to the right in addition to moving the aircraft down.	CHR: 1 Comments: The aircraft was extremely controllable and maneuverable along this axis.
B8	CHR: 10 Comments: Climbing and descending was controllable but there was a tendency to veer off course laterally and difficulty obtaining desired lateral proximity to focal points.	CHR: 1 Comments: (None)
B9	CHR: 4 Comments: It is easy to command roll to move side to side while also attempting to move vertically up and down. I had to	CHR: 2 Comments: The aircraft seemed to drift a couple feet even though the vertical speed indicator read 0 fpm.

Participant	Blue Sim	Red Sim
	keep adjusting for the minor roll commands during the task.	
B10	CHR: 1 Comments: (None)	CHR: 3 Comments: (None)
C1	CHR: 3 Comments: (None)	CHR: 1 Comments: All good, haven't noticed anything bad yet.
C4	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
C5	CHR: 5 Comments: I believe, sometimes the controls were lagging the sensitivity to my command, especially regarding stability. I believe more work can be done to make the control more stable.	CHR: 3 Comments: (None)
C6	CHR: 2 Comments: Up and down controls were unintuitive at first but got better with time.	CHR: 1 Comments: Vertical reposition and hold do not have considerable difficulty.
C6	CHR: 2 Comments: Up and down controls were unintuitive at first but got better with time.	CHR: 1 Comments: Vertical reposition and hold do not have considerable difficulty.
C7	CHR: 4 Comments: The airspeed control is very intuitive and it's nice to be able to set a desired airspeed instead of manually	CHR: 2 Comments: The left inceptor sometimes got stuck in the ascending position even after letting go of it.

Participant	Blue Sim	Red Sim
	maintaining it. The right inceptor will occasionally pick up a slight left or right roll while pulling straight back or pushing straight forward.	
C8	CHR: 5 Comments: Roll instability when descending, easy to overshoot repeatedly.	CHR: 1 Comments: Aircraft performed as expected and held its hover location well.
C10	CHR: 2 Comments: The only issue for me was while descending the aircraft would tend to deviate to my left. I believe this is from me not pulling the stick back perfectly. It was fairly easy to correct. I think most of the issues I had could be attributed to myself getting more familiar with flight controls.	CHR: 1 Comments: I thought this was easier to complete compared to the blue sim.

Table C- 2. Hovering Turn and Hold CHR and participant comments

Participant	**Blue Sim**	**Red Sim**
A4	CHR: 4 Comments: I found it very easy to over control the yaw axis. I frequently found myself trying not to overshoot the point. It may be helpful to establish a standard rate turn or something of that nature to simplify turns using the yaw control.	CHR: 4 Comments: I found that I had to somewhat concentrate on keeping my yaw input constant without altering the climb/decent profile on the aircraft.
A5	CHR: 1 Comments: (None)	CHR: 5 Comments: If attempting to apply a full yaw input the aircraft can't maintain a level flight attitude properly which necessitates a vertical input from me. When using 1/4th or less yaw input I had zero controllability issues.
A6	CHR: 1 Comments: (None)	CHR: 1 Comments: Flight control was easy. This sims flight controls seem easier to manipulate.
A7	CHR: 1 Comments: Directional controllability about the vertical axis is very easy with this aircraft. It takes minimal effort or skill to complete the maneuver and align the aircraft with the boards. Once you develop the ability to judge the rate of turn, you can determine when to release the pressure on the inceptor or determine whether or not	CHR: 2 Comments: (None)

Participant	Blue Sim	Red Sim
	you need to provide further control pressures.	
A8	CHR: 1 Comments: (None)	CHR: 2 Comments: (None)
B1	CHR: 1 Comments: (None)	CHR: 3 Comments: I think it was user error but I found it harder to move the aircraft to the left without gaining altitude than towards the right.
B3	CHR: 1 Comments: I like the yaw input in this simulator (blue) much more than the yaw input on the red simulator.	CHR: 1 Comments: (None)
B4	CHR: 1 Comments: (None)	CHR: 1 Comments: Aircraft movement along the vertical axis was very stable, making it easy to keep the alignment while turning along the vertical axis.
B5	CHR: 1 Comments: This flight maneuver with the control was easy because it was a one-dimensional control.	CHR: 1 Comments: I like the control for the lateral movement on the left with this control because it is not too sensitive to movement but has enough resistance to be effective.
B6	CHR: 1 Comments: Sure, a little training and practice can make anyone better, but this was very intuitive and easy and the aircraft was	CHR: 3 Comments: Felt easy to control, it is easy to accidentally climb or descend a little unintentionally.

Participant	Blue Sim	Red Sim
	very controllable with the perfect sensitivity.	
B7	CHR: 1 Comments: In terms of yaw, the aircraft responds great.	CHR: 1 Comments: The aircraft was both maneuverable and controllable along this axis. I wish that there was some form of turn coordinator that gave information about rate of roll and rate of turn.
B8	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
B9	CHR: 2 Comments: (None)	CHR: 2 Comments: (None)
B10	CHR: 3 Comments: (None)	CHR: 3 Comments: (None)
C1	CHR: 3 Comments: Left and right heading change commands felt differently (very minor difference). It can be just my hand and how I gripped the stick. The twisting nob definitely needs better ergonomics: try making it taller/higher and covering with some non-slippery material.	CHR: 1 Comments: I think this is a common issue of most control sticks which is usually fixed by simply having more flight experience. However, it would be nice to have some mechanical difference (perhaps in resistance or have non-uniform tilt or else) between thrust control and heading to make heading control with altitude hold easier. Otherwise, everything is excellent.
C4	CHR: 1 Comments: (None)	CHR: 1 Comments: Compared to the last version of the red sim, the aircraft feels much more

Participant	Blue Sim	Red Sim
		controllable. For the hover and turn assessment, it feels much easier to turn left and right without accidentally moving in the vertical direction.
C5	CHR: 2 Comments: (None)	CHR: 2 Comments: (None)
Participant C6	CHR: 2 Comments: Turning to left was a bit different experience. I had to make minor corrections to decrease the overshoot.	CHR: 4 Comments: With turn and ascend/descend on the same control, it was sometimes annoying to have to correct the altitude while turning.
Participant C7	CHR: 2 Comments: The only comment I have is that I noticed yawing left and then settling decelerates the yaw rate noticeably faster than yawing to the right.	CHR: 4 Comments: There needs to be some kind of deadzone when turning left and right, so that even when it feels like you are pulling straight to the left or right, it doesn't ascend/descend unintentionally.
Participant C8	CHR: 1 Comments: Excellent control with only yaw inputs, not translation of aircraft to correct.	CHR: 4 Comments: Commanding pure yaw motion without accidentally commanding altitude changes is difficult.
Participant C10	CHR: 1 Comments: (None)	CHR: 1 Comments: I thought this was easier to complete here than in the blue sim.

Table C- 3. Lateral Reposition and Hold CHR and participant comments

Participant	Blue Sim	Red Sim
A4	CHR: 4 Comments: I found it easy to over control the aircraft with the stick. Even when letting go, there was a need to anticipate the hover and I feel that this will come with time, but it was jerky in my experience. It responds best to slow, methodical inputs...	CHR: 8 Comments: Anticipating the stoppage of side stick input was quite difficult in my experience, I found that I often overshot the yellow board and had to fight to keep the nose of the aircraft aligned with the board on roll out.
A5	CHR: 1 Comments: (None)	CHR: 5 Comments: Decelerating from the 10kt velocity was difficult to time, and if you over did it, it was then very difficult to properly line up with the target. Not having any form of speed indication outside your center console when you're staring 90 degrees left was very frustrating.
A6	CHR: 2 Comments: The controls were adequate; however, the position hold throws me off. It feels as though it corrects against me.	CHR: 4 Comments: The right inceptor was slightly difficult to control with forward and lateral flight. It was also slightly difficult to determine when to stop pushing the right inceptor in order to cease lateral flight. Furthermore, the position hold was difficult to adjust to on this task.
A7	CHR: 4 Comments: It was relatively difficult to maintain course guidance along the white line,	CHR: 7 Comments: While the aircraft is controllable, it is significantly more difficult to control is

Participant	Blue Sim	Red Sim
	but small corrections using the left inceptor allowed me to get back "on course" and it was easy to maintain control. The only other minor deficiency appears to be with the sensitivity of the right inceptor. Even the slightest control inputs to translate the aircraft laterally results in a momentary change (loss or gain) in altitude. Fortunately, it is easy to correct.	laterally than vertically, or along the vertical axis. The main issue is that it continues the lateral displacement even after the control pressures are relaxed, and it is very difficult to judge when you should add opposite control inputs to cease the lateral displacement.
A8	CHR: 1 Comments: (None)	CHR: 2 Comments: I prefer the old setting for this task where the aircraft stabilized itself and slowed down for you. This task was still not too difficult, but I think it was a little easier before.
B1	CHR: 4 Comments: I'm not sure if it is user error or the way the aircraft is built but when I returned to the left the alignment with the center line seemed to be off from where I initially started.	CHR: 4 Comments: The aircraft was very sensitive when approaching the hover. This made it hard to pin point the dot on the ""X"".
B3	CHR: 4 Comments: Like mentioned previously, I would change the throttle function to the left controller, and keep only pitch, bank, and yaw on right controller like in forward flight.	CHR: 4 Comments: At very low groundspeed (approx. 1-2 knots), it is difficult to be precise in both forward/backward and left/right movement.

Participant	Blue Sim	Red Sim
B4	CHR: 4 Comments: Similar to the Red sim, the timing of the release to be level with the hoverboard is very specific. Also, the aircraft has a large rocking tendency upon release of the interceptor which may prompt overcorrection.	CHR: 4 Comments: This is a timing issue. The more tries I gave it the closer I was able to time a correct release of control forces., this is something that I think would be perfected with practice. The timing of the release would also depend on the airspeed moving laterally.
B5	CHR: 4 Comments: During this task there was a need to pay more attention than just one dimensional horizontally because of the need to also maintain a lateral presence. Although not considerably difficult in maintaining control, there is a precision that is difficult to maintain (either from the single stick controlling pitch and lateral movement or the stiffness of the stick and fine tuning to get the right amount of input in).	CHR: 5 Comments: Lateral movement is one of the more difficult challenges that is presented with this set of flight controls. I think the resistance on it is too great so there is more room to overcompensate how much speed in the horizontal direction is needed. And because it is tied to the lateral as well, it is easy to get off track if not perfectly going left or right.
B6	CHR: 1 Comments: Very good aircraft controllability. I was confused on the first one, but that is just a simple training adjustment. The aircraft was very good.	CHR: 3 Comments: Okay so I thought the first time was a little rough but then after I figured out how to do it better than it was very controllable. Interestingly... I think my answers on this form compared to last time will show that I believe this sim is much more controllable, less sensitive (in a good way), and overall, a better

Participant	Blue Sim	Red Sim
		aircraft to fly. Pilot workload is significantly decreased
B7	CHR: 5 Comments: There were two problems with this task: • When the right controls were pushed to the left, it would make the aircraft change both in terms of altitude and position. • It is somewhat difficult, although doable with skill, to exactly estimate the aircraft position within the hoverboard and the time it takes the aircraft to stop.	CHR: 5 Comments: The aircraft was both maneuverable and controllable along this axis. I wish that there was some form of turn coordinator that gave information about rate of roll and rate of turn.
B8	CHR: 4 Comments: Altitude fluctuations when banking and movement aft of centerline.	CHR: 10 Comments: Difficult to move about one axis without moving about the other, and difficult to determine when to stop.
B9	CHR: 4 Comments: There seems to be drift backward during both directions but appeared to be more during the left movement (even though no forward or aft movement was given). I had to correct to get back within limits. Additionally, there seems to be drift left or right after the control has been centered even after a couple seconds.	CHR: 4 Comments: There seems to be more drift in the lateral movement compared to yaw and vertical directions, which I had to correct after attempting to come to a hover. It was also easy to give forward or backward movement while trying to do a lateral reposition. These controls seem better for this kind of movement compared to the blue sim in case you do give a forward or backward movement to the controls. In

Participant	Blue Sim	Red Sim
		the case of the blue sim, it could put the aircraft in the ground instead of just forward or backward movement.
B10	CHR: 2 Comments: Being so close to the ground made re-positioning a little harder to accomplish just because you must worry about contacting the ground.	CHR: 2 Comments: (None)
C1	CHR: 3 Comments: Again, I think roll control have some minor overshoot, but it only matters if one is trying to align with the target "exactly".	CHR: 1 Comments: • "Red sim" is far easier and more intuitive than "Blue sim" for me to fly (so far). • I did not notice that "position hold" gets anchored a lot sooner than I would think it should, so it was giving me some confusion at first, but then I just tried to keep it disengaged (with non-zero input) as long as possible. I would prefer it to get active much later (for example, when speed is much closer to zero, so I have already done most of the work and it only keeps aircraft from flying away if there is some wind or else).
C4	CHR: 4 Comments: When moving laterally to the right, forward and reverse corrections were needed.	CHR: 4 Comments: The aircraft continued to move in the direction after right control stick returned to neutral. It was slightly difficult to predict and stop the aircraft without overcorrecting. There was also a slight drift backward from the white

Participant	Blue Sim	Red Sim
		line - which was likely user error - which was slightly difficult to avoid.
C5	CHR: 7 Comments: I was able to control, but maintaining the speed and direction was kind of difficult, for sideways movement.	CHR: 7 Comments: The controls were slow to respond to my instructions.
C6	CHR: 4 Comments: Lateral translations towards left had to be accompanied with altitude adjustment.	CHR: 10 Comments: With the lateral displacement, the joystick seem difficult to control as it was combined with forward/reverse displacement as well. the aircraft overshoot at multiple occasions. It might have been easier with control of lateral and forward/reverse on two separate joysticks.
C7	CHR: 4 Comments: The only comment I have is that I noticed yawing left and then settling decelerates the yaw rate noticeably faster than yawing to the right.	CHR: 8 Comments: The last time I did this task, the horizontal strafing speed was determined by continually holding down the right inceptor, to the left or right. This time it seemed to set a speed and then keep going and required pretty intense "braking" to slow down enough to stay in desired spot. Again, a dead zone for moving the right inceptor left or right would make this far easier.
C8	CHR: 1 Comments: Hover mode is highly reliable and stable in this context. controlling the	CHR: 5 Comments: Countering the hover overshoot is an art form that I am not very good at.

Participant	Blue Sim	Red Sim
	aircraft in lateral motion was intuitive and was considerably easier after only 2-3 practice runs.	
C10	CHR: 4 Comments: When banking to the left/right, the aircraft tended to drift backwards during the initial maneuver. This would stop after 1/4 of the track.	CHR: 1 Comments: (None)

Table C- 4. Pirouette CHR and participant comments

Participant	Blue Sim	Red Sim
A4	CHR: 4 Comments: Controls were robotic in the sense that there was little gradient of input. This made it difficult to execute a perfect maneuver. This could also be attributed to user error and lack of experience in these operations.	CHR: 7 Comments: I had a very strong habit of pulling back on the R stick when I wanted to increase my altitude and this concept came natural to me, yet the left stick was in control of alt. The process of stabilizing the aircraft seems very wobbly to me still, if there was a glass of water on board, I would regularly spill it when transitioning to stand still hover flight simply because the controls are very touchy and difficult to anticipate outcomes with.
A5	CHR: 1 Comments: (None)	CHR: 3 Comments: (None)
A6	CHR: 2 Comments: The first run was better than the second. On the second run I struggled to maintain 6 knots through the last half of the turn. Maintaining heading with yaw (right inceptor) was slightly difficult.	CHR: 4 Comments: The turns to the left were done with minor difficulty. The turns to the right were done with greater difficulty due to having a tendency to climb when pushing on the left inceptor.
A7	CHR: 6 Comments: (None)	CHR: 2 Comments: It is relatively hard to determine the required control inputs to make to maintain the desired radius, but once you determine how to manage the speed, and how to appropriately manage the heading to maintain the position of

Participant	Blue Sim	Red Sim
		the ball in relation to the nose of the aircraft, it is not nearly as difficult.
A8	CHR: 2 Comments: Tough to regulate speed while moving sideways and yawing.	CHR: 1 Comments: I think the new settings made this task a little easier especially when it came to maintaining speed and slowing down at the end.
B1	CHR: 8 Comments: I could not adequately maintain airspeed, altitude, and within the circle especially when I sped up to 6 knots.	CHR: 8 Comments: I got the hang of making the circle around the point. However, I found it very hard to pick up when I should less the controls to complete the circle on time.
B3	CHR: 1 Comments: Like mentioned previously, change the throttle function to the left controller, and keep the right controller as pitch, yaw, and bank like in forward flight.	CHR: 1 Comments: (None)
B4	CHR: 2 Comments: (None)	CHR: 1 Comments: (None)
B5	CHR: 7 Comments: The aircraft is controllable, but the pilot has to constantly think about what to do next because of the minor corrections that need to take place in order for the aircraft to complete the turn. The one thing about these controls is you have to move both the	CHR: 8 Comments: The left pirouette was easier than the right for me because of the way that you move the two controls (coming in together vs the right going away from each other). The main struggle that I experienced was keeping coordinated but also coming to a stop with the speed

Participant	Blue Sim	Red Sim
	top section and bottom section in opposite directions in order to get the desired turn, which makes you have to think a little bit harder about how it is supposed to move.	control stick. I like that it holds relative speed but slowing down and stopping requires an opposing direction which leads to overcompensation and can prevent the aircraft from actually stopping.
B6	CHR: 3 Comments: I believe the aircraft is designed well for this maneuver, but the maneuver is very difficult and takes training. Over time I figured out how to properly complete a nice circle maintaining altitude and alignment, but like I said it takes practice and training. The aircraft is designed well for it though in my opinion.	CHR: 3 Comments: I think the aircraft is controllable, but this is an advanced maneuver. Additionally, I was sitting here thinking wow if this was a real aircraft with passengers, they would all be sick, because it is too sensitive to climbs and descents when you are just trying to maintain directional control. It needs to be less quick to climb and descend when all you're trying to do is turn. Neither side was easier than the other... the aircraft is controllable, but just too quick to climb and descend when all you're trying to do is turn.
B7	CHR: 4 Comments: The only thing that was difficult to control was the lateral speed. I think it would feel more intuitive if the pilot was to put in, say 4 kts, return the controls to neutral, and for the aircraft to maintain the 4kts in the lateral direction. This feels more natural (specifically for fixed wing pilots) than having to maintain a set lateral speed.	CHR: 4 Comments: Initially, the aircraft was easy to control (especially to when pirouetting to the left). Pirouetting to the right, however, was more difficult. The left side control stick is very easy to move up and down, therefore making the aircraft ascend/descend) I also wish that the aircraft had improved static and dynamic stability with regards to pitch and roll. Yaw, however, is fine.

Participant	Blue Sim	Red Sim
B8	CHR: 2 Comments: (None)	CHR: 10 Comments: Several varying factors conflicting with each other at once, due to inconsistent results of inputs.
B9	CHR: 3 Comments: I had to adjust height a couple times even though I only wanted to move laterally and yaw. The twisting motion of the knob could cause a little discomfort if held for a longer period of time.	CHR: 4 Comments: It was difficult to the lateral movement at 4 and 6 knots. At 4 knots, it felt like I had the controls neutral, but it would slow down gradually so I would need to input a small bit of control and then back to neutral to hold 4 knots. This was similar for 6 knots. Controlling this movement with both hands help lower some of the workload for each hand individually compared to the Blue Sim. Though the twist of the hand seems intuitive.
B10	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
C1	CHR: 3 Comments: Again, I think roll control have some minor overshoot, but it only matters if one is trying to align with the target "exactly".	CHR: 1 Comments: • Still way better than Blue sim but has a similar issue of keeping altitude when trying to fly the maneuver. • Position control is strange, would prefer it to be inactive. Some drift to a random location is present where I don’t actually have an idea of where is the point the position hold is trying to bring me to (especially since the anchor

Participant	Blue Sim	Red Sim
		point can be dropped a lot earlier than I expect it). • Regarding the altitude/throttle input: perhaps it can help to have a wide/wider dead-zone on the alt. channel for the stick input (but not for the heading input) of at least 7-10 degrees.
C4	CHR: 1 Comments: I found it slightly difficult to keep a steady turn speed with the right controller - as if the twisting mechanism is too resistive.	CHR: 3 Comments: I found it more difficult to maintain 4knots than 6 knots. When coming to a stop it was easy to over-correct and not end up in the desired location angle.
C5	CHR: 9 Comments: This task involved three different controls simultaneously. It was intensely difficult to control all three directions simultaneously.	CHR: 4 Comments: Some controls were slightly slower to respond. Else it was fine.
C6	CHR: 8 Comments: Yawing while moving to left or right was hard. I had to constantly make sure I was inside the markers and make sure my heading and altitude were correct.	CHR: 10 Comments: Control for altitude and turn were together so it was extremely hard to keep it level. Felt like I flew being drunk the whole time trying to control it.
C7	CHR: 1 Comments: The controls were tuned very well IMO, except for a minor complaint, it was my own human error that took some adjustments. Pirouetting to the left was significantly more challenging than pirouetting to the	CHR: 8 Comments: The right inceptor setting a speed doesn’t seem to be consistent. I set a speed, and it holds that speed for a few seconds, then it starts decelerating, so i try and correct it, but if I move the stick more than a minute amount it

Participant	Blue Sim	Red Sim
	right. When pirouetting to the left I found it more challenging to maintain altitude, the right inceptor seemed less stable when rolling to the left, in the sense it would be much easier to accidentally push it forward or backwards slightly, changing my altitude, than when rolling right. To the right it seemed much more stable.	accelerates like crazy, either to the left or right.
C8	CHR: 2 Comments: There is an ideal lateral movement to yaw rate ratio in there, and I believe I reached this at least briefly. That was a stable flight condition that I felt in control of. Flying by looking at references instead of staring at the red tape significantly improved my control. Automated altitude hold would have been a helpful tool.	CHR: 1 Comments: Lateral speed required very little input to maintain at a constant speed, once moving this task was almost completely rudder input.
C10	CHR: 2 Comments: It took me a few attempts to get use to tilting the control stick while turning the top for yaw control. After a couple runs, it felt much easier to do.	CHR: 1 Comments: (None)
	CHR: 1 Comments: (None)	

Table C- 5. Precision Hover CHR and participant comments

Participant	Blue Sim	Red Sim
A4	CHR: 4 Comments: Something that just crossed my mind is "Why are the controls not setup similar to that of a DJI drone. I would think that in hover mode that would be the most user-friendly option. That said, I have zero rotorcraft/helicopter experience, but it was on my mind.	CHR: 1 Comments: (None)
A5	CHR: 4 Comments: Without changing the heading this task is exceedingly frustrating due mostly to inexperience on my end managing the throttle with no real "brakes" so you had to gauge the momentum properly to get over the target box in the X/Y correctly. This required consistent throttle inputs to arrest my momentum during all three attempts.	CHR: 3 Comments: (None)
A6	CHR: 1 Comments: Both runs were adequate, however, the second was done in better time. Controls felt good. Position hold did not seem to interfere. I did have to correct for altitude each run.	CHR: 2 Comments: This task was able to be performed with slight difficulty. The two factors that made it difficult was the continued lateral movement after releasing on the right inceptor and the position hold throwing me off.

Participant	Blue Sim	Red Sim
A7	CHR: 2 Comments: This maneuver is very difficult because of the constant manipulation of both inceptors. Even if you have them set in the same position, it does not seem possible to complete the maneuver within the specified parameters because it requires constant manipulation. In my opinion, it would take extensive practice to be able to adequately complete the maneuver.	CHR: 7 Comments: It was very difficult to maintain aircraft control when attempting to recover from the "crab" into the hover. While it was easy to initiate the maneuver, it was hard to place the aircraft directly over the target area initially.
A8	CHR: 1 Comments: (None)	CHR: 4 Comments: For this task, I prefer the old settings because they made it easier to stop and align with both hoverboards simultaneously. It was somewhat difficult to stop precisely aligned with the boards with the new settings.
B1	CHR: 9 Comments: I struggled with maintaining altitude at points and often over then undershooting the aiming point.	CHR: 4 Comments: At first, I had problems over shooting the hover spot but it got better with each attempt.
B3	CHR: 7 Comments: I had the same problem with the red simulator. When below about 2 knots ground speed, the aircraft is programmed to auto center, instead of keep moving in the same direction. This can get very	CHR: 4 Comments: Same as before, it was quite annoying trying to make small adjustments for both forward/backward and left/right movement.

Participant	Blue Sim	Red Sim
	frustrating when you are trying to be very precise with your movements and controller inputs.	
B4	CHR: 4 Comments: Adding a small amount of forward thrust resulted in an immediate forward motion that was somewhat excessive.	CHR: 4 Comments: This is a timing issue again. The release for the controls needs to come at an exact moment to make sure the pilot does not blow through the course. I got better at it each time and was able to align it quick during the last trial.
B5	CHR: 2 Comments: When performing this maneuver, it seems easier on the pilot task load because they are different controls for each of the dimensions that are used.	CHR: 4 Comments: I am not sure exactly what could be improved. I think a mechanism to help with stopping the aircraft so that there was less of the back and forth to get it in the squares and just let it come to a rest would be easier because then it would be anticipated rather than just hoping it comes to a rest after meddling back and forth so much.
B6	CHR: 2 Comments: Good controllability. Training will always make it better, but overall, pretty easy with this aircraft to fly this maneuver.	CHR: 2 Comments: Easy task and easily controllable. No issues here. Maybe could be slightly less sensitive when coming to a stop or making small corrections, but overall good and much better than last time.
B7	CHR: 3 Comments: In most other ways, this sim feels more intuitive as a pilot than the last. However, along a diagonal line it is	CHR: 4 Comments: When the yoke was pushed at a 45-degree angle, I felt as though the aircraft

Participant	Blue Sim	Red Sim
	difficult to mentally divide the task of having to apply longitudinal controls in the left hand and lateral controls in the right.	moved faster laterally than it did forward and aft.
B8	CHR: 1 Comments: (None)	CHR: 4 Comments: Difficult to determine when to stop and correct for further movement horizontally.
B9	CHR: 4 Comments: The aircraft takes time to slow down from 6-10 knots in the forward direction, so it would take practice to know when to let off the throttle control to have it stop at the right spot. I had to keep correcting backward to the right position. This is a consequence of having the controls on separate handles also.	CHR: 4 Comments: It was difficult to hold exactly a 45-degree angle at 6 to 10 knots and come to a stop without having to correct for overshooting the target in both directions. The forward and sideways movement on a single control stick seems more intuitive compared to the Blue Sim with the two separate control sticks. The previous version of the Red Sim seemed to come to a stop when the right control stick was set to neutral. I seemed to better control the aircraft with that instead of having to put a good amount of opposite direction input to stop the movement.
B10	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
C1	CHR: 3 Comments: Position hold needs some minor tweaking to get rid of the saddle-like motion there is some minor	CHR: 1 Comments: (None)

Participant	Blue Sim	Red Sim
	overshoot for roll and forward commands.	
C4	CHR: 1 Comments: I found that I did not need to move the left controller forward very much compared to the right on this task. It took a few tries to learn the correct proportions for each stick to move in 45 degree forward.	CHR: 5 Comments: The precision hover is easier in the red sim than the blue sim. Although it was still very difficult to come to a complete stop without need for corrections. Starting off in the correct direction was seemed also difficult to get consistent. In my opinion, adding a grid on the "INCEPTOR POS/ CLAW SUMMARY" graph screen and the ability for the indicator to move along with the forward and backward movement of the controller would make this task much easier.
C5	CHR: 8 Comments: The world load was quite a lot as the diagonal direction required multiple movements. Some automatic stability control would be better.	CHR: 4 Comments: Again, slow to respond to controls. The side wise movement is little weird to control.
C6	CHR: 2 Comments: Had to make sure my throttle, altitude and heading was correct. Rest was good.	CHR: 3 Comments: It wasn't as disorienting as the ones before. But still a bit harder to control. Any maneuver that does not require control of both joysticks feel easier.
C7	CHR: 5 Comments: The crab maneuver was very challenging because the airspeed acceleration with the left inceptor	CHR: 8 Comments: The cruise control setting on forward and horizontal speed is really challenging to figure out and isn't very

Participant	Blue Sim	Red Sim
	was not very intuitive and seemed exponential instead of linear. I started to figure out somewhat of a balance on my last attempt.	intuitive. Had to make a ton of corrections just to get the plane to stay in the desired spot.
C8	CHR: 2 Comments: Crabbing without requiring yaw input is amazing but strange. This situation makes me with forward/aft was on the y axis of the joystick instead of the left hand, it would make it easier to coordinate lateral and forward motion in this context.	CHR: 1 Comments: Very simple to command diagonal motion since the directions are on the same joystick.
C10	CHR: 2 Comments: Forward control felt very sensitive initially, but after adjusting to that, the task was much easier to complete.	CHR: 1 Comments: It takes a little getting used to maneuvering to cancel out horizontal velocity, but I think I prefer this compared to blue sim.
	CHR: 1 Comments: (None)	

Table C- 6. UAM Mission TransToFwd CHR and participant comments

Participant	Blue Sim	Red Sim
A4	CHR: 4 Comments: I found it difficult to implement rudder usage into my turns based on the sensitivity of the yaw control. It seemed as if any time I would make a rudder input, it would make things considerably more difficult.	CHR: 4 Comments: As previously stated, the controls are quite touchy, and I found it difficult to anticipate control movements especially close to the ground when it becomes important for precise inputs.
A5	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
A6	CHR: 1 Comments: Transition felt stable. Flight characteristics felt stable and easy to manipulate.	CHR: 3 Comments: Initially learning what inceptor input related to each flight control was slightly difficult and resulted in slight oscillations of a vertical speed and lateral movement of the aircraft. Once I understood the controls it overall was not too difficult. Transition to forward flight in this sim seemed slightly harder to control.
A7	CHR: 1 Comments: The transition from a hover to forward flight is very smooth and easy to complete. The only deficiency I noticed was when the lift propulsors stopped, and the propeller in the rear of the aircraft began operating, the transition in terms of flight control authority did not seem quite as smooth as it could	CHR: 1 Comments: overall, the real-world application during the last task was significantly easier to complete as opposed to relatively static maneuvers/tasks.

Participant	Blue Sim	Red Sim
	be. However, overall, it is very easy to transition to forward flight – the minor deficiency did not prevent me from maintaining positive control of the aircraft.	
A8	CHR: 4 Comments: When speeding up, path priority and speed priority kept switching back and forth which threw me off a bit.	CHR: 2 Comments: At one point during the transition and climb, I saw the speed priority thing pop up and it caused the aircraft to pitch down aggressively, that is the only minor deficiency I noticed.
B1	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
B3	CHR: 2 Comments: Very well put together. The transitions between hover and forward flight can be a bit weird, however that just takes getting used to.	CHR: 1 Comments: I would change the throttle input to something else and keep the bank and pitch on the control stick like every other aircraft in the world. Otherwise, very well done, aircraft flies very well.
B4	CHR: 3 Comments: When transitioning to forward flight, there may need to be more notifications and advisories to allow the pilot to prepare for better control inputs ex) audible alerts. A systematic approach such as a checklist for the steps to transition into forward flight can help greatly. Also, the pink airspeed arrow was not showing an adequate airspeed to	CHR: 1 Comments: (None)

Participant	Blue Sim	Red Sim
	continue in a forward climb, therefore I added more airspeed than recommended.	
B5	CHR: 2 Comments: (None)	CHR: 2 Comments: Overall controlling the aircraft from hover to forward flight was well. Just have to remember that the right control stick is for speed while the left is for altitude (which I would sometimes try to use one for the other, but it was not an unsafe action). Most of the transition is straightforward; there is good movement without precision but enough to get to the flight plan accurately.
B6	CHR: 1 Comments: Very controllable - but not too sensitive. Also, very intuitive.	CHR: 1 Comments: Takeoff and transition to forward flight was great. Easy, intuitive, controllable, and I wouldn’t change anything or have any recommendations.
B7	CHR: 6 Comments: The aircraft was controllable, and the mission was accomplished with minor control corrections, however, the aircraft had multiple oscillations in terms of vertical speed (1,500ft+ within a matter of milliseconds). In real life, this is not survivable for passengers, and all occupants would endure significant g-loading. Second, there was an annunciator that got stuck during the transition	CHR: 1 Comments: The aircraft smoothly transitioned from vertical flight mode to forward flight mode. Really no additional comments other than I wish the ""FLIGHT"" operating mode indicator was broken down into both forward and vertical flight for easier indications. Think that this would increase pilot awareness of operating mode.

Participant	Blue Sim	Red Sim
	(speed priority + path priority) it seemed to be some sort of a glitch/oscillation between modes.	
B8	CHR: 4 Comments: Lag between pitch input and output.	CHR: 2 Comments: (None)
B9	CHR: 5 Comments: When transitioning between vertical to forward flight, there is a point around 120 kts forward speed that requests a pitch up. However, during that phase, a pull up was not possible or it would oscillate from an exaggerated pitch up to no pitch even though I had little input change. This could be caused by the controls changing from continuous input to hold a speed or pitch to using input to set a pitch or speed.	CHR: 3 Comments: The takeoff controls seem intuitive, and it is very easy transition from vertical to forward flight. The controls of airspeed on the right stick seems counter intuitive once it is in forward flight mode as I found myself wanting to pull back to increase vertical speed which resulted in a decrease in forward speed.
B10	CHR: 3 Comments: (None)	CHR: 2 Comments: (None)
C1	CHR: 1 Comments: I think the guidance computer was trying to guide me right into the wall the very first time. Otherwise, great.	CHR: 1 Comments: All great!
C4	CHR: 1 Comments: (None)	CHR: 1 Comments: (None)
C5	CHR: 3 Comments: (None)	CHR: 4 Comments:

Participant	Blue Sim	Red Sim
		The aircraft rate of ascent was not as fast as i intent to give as input.
C6	CHR: 3 Comments: (None)	CHR: 3 Comments: Transition to forward flight was easy for me. It does not require too much effort from my side.
C7	CHR: 3 Comments: "Transitioning to forward flight was relatively intuitive and easy. It was definitely an adjustment from direct upwards and downwards with the right inceptor to affecting the pitch angle with the right inceptor. "	CHR: 3 Comments: The cruise control is not intuitive.
C8	CHR: 5 Comments: At the 150 knots section, there is a runaway increase in vertical speed if the nose is pushed slightly too high, requiring a correction and then safeguarding to not pass that point again. This occurred twice one after another in my run.	CHR: 1 Comments: Transition was almost unnoticeable: incredibly smooth and in-control feeling.
C10	CHR: 2 Comments: I believe the issues I had on departure were all user related. The aircraft responded well to inputs and felt easy to control.	CHR: 1 Comments: (None)

Table C- 7. Heli Approach CHR and participant comments

Participant	Blue Sim	Red Sim
A4	CHR: 4 Comments: Transition from airplane to hover mode was difficult to control. I often found myself chasing the control bars on the approach to land and found it better to ignore them and look outside.	CHR: 4 Comments: The handing of the aircraft in cruise mode was rough. The concept of the left stick controlling altitude was quite foreign and I often caught myself using the R stick to try and change altitude, the heli landing made sense in terms of control inputs.
A5	CHR: 2 Comments: The speed transition from forward flight back to the hover is not very intuitive as the auto throttle in FWD flight holds the commanded speed, but then when you transition into the vertical that system disengages, and you have to manually do it. Overall excellent control setup for the task.	CHR: 10 Comments: Aircraft entirely over speed with no real way of slowing on the descent profile request by the avionics. Had no real way of slowing even with following its speed prompting and it just would not stop nor transition into a hover to enable a landing. Having the throttle be the same inceptor controlling my course made speed management very difficult. Combined with my inexperience in rotor wing aircraft this was not a good set up for me personally.
A6	CHR: 3 Comments: While transitioning to a lower speed the flight control command became sensitive. I got into an oscillation of side to side; however, it was recoverable with smaller control inputs. Once hover mode activated the control command felt more stable.	CHR: 2 Comments: Maneuvering with the right inceptor was slightly difficult to control and keep track of due to the adjustment of speed and movement in the same control. Landing, however, was not that difficult and could be done fairly easily. Landing in this sim seemed easier than the other.

Participant	Blue Sim	Red Sim
A7	CHR: 2 Comments: On my first approach and landing, for some reason I was unable to maintain positive control of the aircraft and shot right past the designated yellow square. After the sim was reset for an approach and landing, and even during the second circuit, I was definitely able to maintain positive control of the aircraft and maintain the designated speeds, and altitudes prescribed by the flight path manager, allowing me to land on the designated box. One of the main recommendations/comments I have for this system would be to include some form or fashion of a Horizontal situation indicator (HSI) or include a course deviation indicator (CDI) on the existing heading indicator. That will give the pilot an accurate representation of left or right deviations off of the course, as opposed to just the flight director on the PFD.	CHR: 2 Comments: The transition from en-route to approach was slightly more difficult. It was harder to reestablish control after the aircraft transitioned from forward flight to vertical.
A8	CHR: 4 Comments: Roll was somewhat unstable when slowing down in hover mode. Small roll inputs would cause a lot of oscillation.	CHR: 1 Comments: (None)

Participant	Blue Sim	Red Sim
B1	CHR: 2 Comments: Slowing down the aircraft was a bit hard as both times I overshot the approach area. However, I improved greatly from the first approach to the second.	CHR: 4 Comments: On the first approach, I struggled with landing the aircraft. I did not realize that I needed to use the left and right stick. The left to enter ground mode and right to reduce the speed to zero.
B3	CHR: 2 Comments: Like said previously, very well put together. The transitions are a bit weird at first, but with practice they become more manageable and predictable. I just had to keep in mind small bank movements or else you'll get out of control.	CHR: 1 Comments: Same thing I mentioned previously. I would make pitch and bank on the control stick and put throttle on a different controller. Otherwise, very well made and the aircraft flies very well.
B4	CHR: 5 Comments: I do not know if the simulation airspeed is taking into account forward, or real airspeed regardless of movement on any axis. The transition was somewhat difficult to vertical mode because of the excessive descent rate required. Additionally, the airspeed was not slowing down quick enough to figure out a good sight picture for an optimal landing point.	CHR: 7 Comments: The directions for transitioning from forward to hover mode may have been unclear.
B5	CHR: 2 Comments: On the arrival phase, the only portion that was not as simple was coming in on the final approach	CHR: 2 Comments: Besides crashing the first time because I got a little bit off the airspeed at the end, the approach was stable (especially the

Participant	Blue Sim	Red Sim
	sequence after the barrier. Going from airspeed to altitude increased the workload because you are focusing more on both to make it to the touchdown spot without wanting to be short or go over.	second time). The flight director guiding is helpful to know how much input to use to transition to the approach phase. It is a little difficult to know how much airspeed input is needed because it would hold the airspeed but at the end, I had to put constant pressure to maintain 10-15 knots (whereas before I could be at it and it would hold on its own). Maybe because it was slow and continuing it would not hold but I'm not sure. Altitude was not a problem during the approach stage, and it was helpful to have that flight director as well. Controls for the altitude are well (I like the setup of the left side controls over the configuration of those on the right).
B6	CHR: 2 Comments: Very controllable, BUT I found that the flight director does not really set you up to land at the correct time at the approach area, so after crossing the obstacle I had to plan on my own how to hit the point. The first time I overshot because I was following the flight director, but the second time I figured it out. Maybe the flight director can be adjusted I do not know, but the controllability was really good.	CHR: 4 Comments: I think it was so much better and way more controllable than last time on landing. It seems recommendations really were applied because I have noticed today that all my major issues from last time have been resolved or significantly improved. The last aircraft is one I would never set foot on in real life. This one I would with training, and I think that says a lot. I still think the controls could be a little less sensitive (especially in slow phases of flight such as landing) but honestly this is solid. I don't have many recommendations. It's intuitive and controllable. Just a little

Participant	Blue Sim	Red Sim
		less sensitive maybe on the directional controls and vertical controls.
B7	CHR: 2 Comments: AC was controllable, and mission accomplished. Only issue was in terms of vertical and horizontal guidance. Guidance took the aircraft about 40-50ft left of the ""landing pad"". Other than that, this phase had no issues and was quite easy to fly.	CHR: 10 Comments: On the approach to landing phase, there were multiple problems: 1. The aircraft stalled multiple times during the transition. To avoid this, an angle of attack indicator should be installed in the aircraft. There also needs to be better indication as to which mode the aircraft is flying in (vertical/forward flight). 2. The aircraft is extremely difficult to control PRECISELY. This is due to the inherent instability of the aircraft. If this aircraft is to be used for transportation/training purposes, the maneuverability of the plane should be replaced with stability- both dynamic and static.
B8	CHR: 4 Comments: Minor disconnect between input and output, necessary to anticipate corrections	CHR: 2 Comments: (None)
B9	CHR: 4 Comments: Q3- Again during the transition when the lift motors turn on, there is an instance where pitch down (or descend) input does not produce a descent. Once it slows down enough, it is controllable as expected. Q4- During the forward	CHR: 4 Comments: It was difficult to reduce forward speed, turn, and descend all at the same time. The approach procedure requires zero vertical speed after clearing the wall to enter the hover mode. It seems that it should still reduce forward speed until 0 even while descending. Once I was able

Participant	Blue Sim	Red Sim
	flight, I think it would be better to keep the controls continuous input to hold a bank or pitch. This seems more appropriate. Also holding a turn or bank for a while can make a person seem like they aren't turning anymore without external references. Therefore, a continuous input to hold bank seems safer.	to figure that out, it was a fairly easy transition from forward to vertical flight to land.
B10	CHR: 8 Comments: I struggled to follow the flight director on the final approach. I also struggled to pitch up when it began to sink.	CHR: 1 Comments: There was some difficulty in the descent portion of flight while trying to use the right-hand inceptor to slow down as well as turn. It was manageable but it provided a little extra difficulty. The Red sim using the 2 different control sticks to pitch, and bank made controlling the aircraft a little more complicated than just the one in the Blue sim. Having the thrust controlled on the same stick as the bank control makes controlling the aircraft near the ground a little easier but when descending and trying to set up for landing it can be challenging.
C1	CHR: 3 Comments: When airspeed is around 50-60knots, and I give about 5-10 degrees pitch down, any small lateral/roll command causes seem a little unstable and you have to fight	CHR: 1 Comments: 1. when I was flying the blue sim, I had an issue when aircraft was getting slightly unstable in roll during approach (at certain airspeed, don't remember). With the red sim, I have not yet encountered this issue, but the approach

Participant	Blue Sim	Red Sim
	the control system a bit to maintain roll/heading.	is also different now... 2. Nav. is still trying to kill me, or I just did not understand how it works: apparently, I should not try to match the commanded airspeed with the one it wants me to follow, but command whatever it takes to bring the real airspeed to the one suggested by the Nav. Otherwise, this version is a lot easier to fly than the blue sim.
C4	CHR: 1 Comments: (None)	CHR: 1 Comments: This task was much easier to complete than last time I did the red sim. Overall, I prefer the controls of the red sim over the blue sim. After transitioning to hover, the control instructions for speed were insufficient to get to the landing pad. I had to go over the recommended speed to approach properly and land.
C5	CHR: 8 Comments: Controlling speed with altitude is slightly tricky without lot of practice. Some automatic controllability over at least one parameter would make it easier.	CHR: 9 Comments: Doing multiple inputs to control the landing was intensely difficult as both speed and direction needed to be controlled.
C6	CHR: 10 Comments: Approach to land was difficult. Felt dizzy. Had to constantly make sure I was within the magenta marker; it was the most difficult task.	CHR: 10 Comments: It was difficult. I had to control all three areas of joystick power, altitude, turning. It was a lot harder than the ones before. I would take Blue sim over red sim if I had to do it again. It seems more

Participant	Blue Sim	Red Sim
		intuitive and less cumbersome for me. Overall, it was an okay experience with the red sim.
C7	CHR: 3 Comments: The landing was significantly more challenging, IMO because the bars and purple flight speed marker were not very intuitive. I tried to follow the speed and bars exactly and overshot the landing every single time. It was only when I intuited an airspeed and descent angle was I able to land perfectly with very little adjustments.	CHR: 9 Comments: The braking seemed to be nonexistent. I set the green arrow to the same speed as the magenta one, but the plane decelerated extremely slowly, and on first approach I went clear past the landing zone. On the second try I ignored the magenta arrow and started braking way in advance and was able to land adequately.
C8	CHR: 3 Comments: downward view is limited, making the landing target difficult to see during final stages of landing, and difficult to reacquire if passed over. I experienced a guidance error where the magenta cross instructed me to circle waypoint CDS three times. I had to disobey the guidance and reapproach the waypoint to proceed to the next. The moment of initiation of the wing propellers is a little awkward/shaky but did not require significant input control to correct.	CHR: 1 Comments: Less descent instability in flight mode than in hover mode.
C10	CHR: 2 Comments:	CHR: 1 Comments:

Participant	Blue Sim	Red Sim
	Like departure, I felt like most of my issues were user related and not with the aircraft. Aircraft was easy to control after being familiar with the maneuver.	It would have been better to have some type of map markers to fly around. Following the magenta cross made it a little difficult to recover after getting off profile and I lacked the awareness of exactly where I was in relation to the landing area after my error in getting off profile. The aircraft felt great to fly after getting use to altitude controls.