PILOTED SIMULATION EVALUATION OF AUGMENTED CONTROL MODES AND MODE REVERSIONS ON AN EVTOL AIRCRAFT

Joseph F. Horn
Grant Lee

The Pennsylvania State University
University Park, PA United States 16802

Dakota Musso
Emily Vo
Michael P. Jones
Systems Technology Inc.
Hawthorne, CA United States 90250

ABSTRACT

Control laws were designed for a Lift + Cruise eVTOL aircraft and evaluated in piloted simulation. The control laws feature an Attitude Command baseline control mode and selectable augmented modes intended to achieve Simplified Vehicle Operation. Translation Rate Command / Position Hold (TRC/PH) is used in hover / low speed and a Unified flight control is used in forward flight. The simulation test applied the Simulation based Automation and Failure Evaluations (SAFE) process to evaluate the controller in baseline mode, augmented modes, and fault cases where the control reverts to baseline mode. The test found that the TRC/PH controller provided level 1 handling qualities in a Precision Hover, while degrading to Level 2 with a mode reversion. The SAFE process was able to reveal handling qualities deficiencies in a heliport approach, and the Unified control law was improved for both nominal operation and during mode reversions.

NOTATION

Symbols

$\mathbf{A}, \mathbf{B}, \mathbf{C}$	Linear Model State Space Matrices
d	Disturbance on plant output
e	Tracking error
J	Rotational inertia, kg-m^2
K	Control gain
K_p, K_I, K_D, K_{II}	Proportional, integral, derivative, double integral gains
$\mathbf{M}, \mathbf{b}$	Mixing gain matrix and bias vector
p, q, r	Body axis angular rates, rad/s
Q	Torque, N-m
$\mathbf{r}$	Reference input vector
s	Laplace operator
u, v, w	Body axis velocities
V, V_z	Airspeed and vertical speed
$\mathbf{x}, \mathbf{u}, \mathbf{y}$	State, control, and output vectors
δ	Control surface deflection
ϕ, θ, ψ	Roll, pitch, yaw Euler angles, rad or deg
ν	Pseudo-control
τ, ω_n, ζ	Time constants, natural frequency, damping ratio
Ω	Rotor speed, rad/s

Acronyms

ACAH	Attitude Command / Attitude Hold
AFCS	Automatic Flight Control System
BWL	Bedford Workload Rating
CV	Controlled Variable
DI	Dynamic Inversion
FPA	Flight Path Angle
HQR	Handling Qualities Rating
HQTE	Handling Qualities Task Element
HUD	Heads-Up Display
IFES	Integrated Failure Evaluation Scheme
INS	Inertial Navigation System
MOC	Means of Compliance
MTE	Mission Task Element
PH	Position Hold
PID	Proportional-Integral-Derivative
PIOR	Pilot Induced Oscillation Rating
SISO	Single Input / Single Output
SVO	Simplified Vehicle Operations

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TRC	Translation Rate Command
VTOL	Vertical Takeoff and Landing

1. INTRODUCTION

There have been numerous aircraft configurations proposed under the broad category of Advanced Air Mobility (AAM), including electric-powered Vertical Takeoff and Landing (eVTOL) configurations designed for operation in urban environments. For high volume traffic in urban areas, it is expected that the aircraft will require Simplified Vehicle Operations (SVO) with highly augmented flight controls that result in low pilot workload with minimum required pilot training [1]. It is likely that such control schemes will need fallback modes that engage in the event of system faults related to sensor failures or loss of GPS ("mode reversion"). These fail-safe modes, and the accompanying transient effects during reversion, might provide less stability and result in higher pilot workload but ensure the aircraft is still safe and controllable. It will be critical that the flight controllers are designed to provide sufficient handling qualities and graceful mode transition, and that there be processes to certify these systems for use in the National Airspace. This includes certification of both the primary modes and reversion to fail-safe modes. System Technology, Inc. has worked with the FAA and NASA on Means of Compliance (MOC) using Handling Qualities Task Elements (HQTEs) and display technologies to aid in assessment [2, 3]. Piloted simulation is a valuable tool for both assessing compliance and improving the flight control performance and handling qualities based on operator feedback.

The objectives of this study are as follows: 1) Investigate novel flight control architectures that achieve Simplified Vehicle Operation, exploring both nominal operations and mode reversions to lower levels of augmentation. 2) Apply a simulation-based process for efficiently conducting HQTEs, evaluating handling qualities, and improving flight controller design. 3) Investigate the potential benefits and challenges of increased levels of autonomy and augmentation in controllers for eVTOL AAM aircraft including effects of mode reversions.

The study is applied to a generic eVTOL aircraft designed in the Lift + Cruise configuration. A flight controller was designed using a Dynamic Inversion architecture to meet Level 1 predicted handling qualities according to a combination of specifications in MIL-DTL-32742 and MIL-STD-1797B [4, 5]. The controller has a baseline control mode with Attitude and Vertical Speed Stabilization and selectable augmented control modes that feature Translation Rate Command, Position Hold, Flight Path Command, Altitude Hold, and Airspeed Hold. The controllers were tested in piloted simulations and subjective ratings were assigned for the baseline control modes, for the augmented control modes, and for cases where the controller reverts from the augmented to the baseline control mode mid-task.

2. AIRCRAFT CONFIGURATION AND SIMULATION MODEL

The eVTOL aircraft used in this study is a notional Lift + Cruise configuration capable of vertical flight and conversion to a fixed-wing configuration at higher airspeeds. This is a five-passenger, 7000 lbs configuration with four lift rotors and a pusher propeller. It has been used in previous studies at Penn State University and is referred to as PSU Reference Aircraft 2 [6]. Table 1 lists some of the key properties, and the configuration is illustrated in Figure 1. This aircraft is effectively a compound rotorcraft that flies as a VTOL rotorcraft in hover and low speed in which the lift rotors are used for both lift and primary flight control. The pilot can accelerate forward using the pusher propeller, and as airspeed increases the wing carries the lift of the aircraft. Once fully converted to airplane mode, the lift rotors are stopped and control is achieved entirely through fixed-wing control surfaces (ailerons, elevators, and rudders).

The aircraft is modelled using the PSU-DEPSim (Distributed Electric Propulsion Simulation) software [7]. This software was developed to simulate rotorcraft that features distributed electric propulsion, i.e. multiple rotors used for lift, propulsion, and primary flight control. The software and underlying model are described in detail in Ref. 7. PSU-DEPSim provides a complete state-space representation of the non-linear equations of motion, rotor blade dynamics, finite-state rotor inflow, electric motor dynamics, and actuator dynamics. The model is developed in MATLAB and implemented in Simulink, with the controllers, motors, and actuators modeled with Simulink block diagrams. The Simulink model is then autocoded to C and complied for use in real-time piloted simulations.

The aircraft is assumed to have collective pitch control of all four lift rotors and the pusher propeller.

It uses variable collective pitch for primary flight control while the motors use an RPM governor to regulate the rotor speeds at prescribed set points. This deviates from common practice in these types of aircraft, but this approach simplified the modeling and control design. It is expected that the control design and analysis methods used in this study could also be applied to an eVTOL aircraft with variable RPM control.

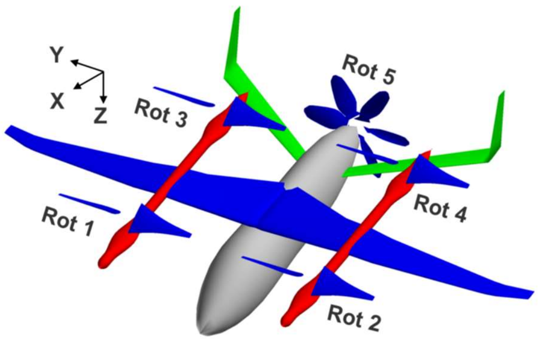

Figure 1 Notional Lift + Cruise eVTOL Configuration (PSU Reference Aircraft #2)

Table 1: Properties of Main Components on PSU Reference Aircraft #2

COMPONENT	PROPERTIES
LIFT ROTORS (4) *	6.25 ft radius
	2 rigid blades
	Nominal RPM in Hover = 1000 RPM
	Control: Fixed-Pitch, Variable-RPM
	Propulsion: Twin Electric motors, 1500 N-m maximum torque each
CRUISE PROPELLER	5 ft radius
	6 rigid blades
	Governed RPM = 1300 RPM
	Control: Fixed RPM, Variable-pitch
	Propulsion: Twin Electric motors, 1500 N-m maximum torque each
WING	50 ft span
	Aspect Ratio = 23.4
	Control: ailerons (2)
HORIZONTAL TAIL	22 ft span
	35 deg sweep
	Control: elevators (2)
VERTICAL TAILS (2)	Twin 6 ft Vertical Tails
	10 deg sweep
	Control: rudders (2)

*All lift rotors have a 3° inboard tilt, and the forward rotors have a 6° forward tilt

All rotors on the aircraft are assumed to be rigid, therefore there are no rotor flapping dynamics. The aircraft state consists of the 12 rigid body states of the aircraft and three-state dynamic inflow for each of the five rotors for a total of 27 aircraft states. In addition, first order actuator models are used for the 11 control effectors on the aircraft: collective pitch on each rotor (5), wing flaperons (2), elevators (2), and rudders (2). All actuator models have a corner frequency of 40 rad/s with rate limits of 30 deg/s. The aircraft is assumed to have twin electric direct drive motors for each rotor, but each of the twin motor pairs are modelled as a single 1st order torque response system. A model following controller with PI compensation is used to follow motor speed commands, as shown in Figure 2. Note that torque limits are also imposed but not shown in Figure 2.

An airspeed-scheduled control mixing scheme is used to map the primary control axes to the multiple effectors on the aircraft. The mixing uses an affine mapping in which the mixing gain matrix and bias vector are scheduled with airspeed. The control effector vector, $\boldsymbol{\delta}$, is computed as follows:

$$\boldsymbol{\delta} = \mathbf{M}(V)\mathbf{u} + \mathbf{b}(V) \quad (1)$$

where the vector $\mathbf{u}$ contains the five flight control inputs computed by the AFCS: roll, pitch, vertical, yaw, and forward thrust controls. The mixing gain matrix, $\mathbf{M}$, varies with airspeed and phases out the use of lift rotors in flight control as the aircraft transitions from VTOL mode into airplane mode. The mixing follows a similar scheme as used in Ref. 5. For this configuration, the aircraft transitions to airplane mode between 85 and 90 knots forward airspeed. In the transition range, the mixing gains from lateral, longitudinal, vertical, and yaw control to lift rotor collective fades to zero, and the rotor RPM set point drops to 0.

The model of the airframe dynamics is in state space form and is fully linearizable using small perturbations and finite differencing. These linearized models are used in control design, as described below, where the linear model is reduced to 8th order, neglecting inflow, actuator, and motor dynamics. In addition, the Simulink model, which incorporates airframe, actuator, and motor dynamics along with the Automatic Flight Control System (AFCS), can be linearized to conduct linear system analyses on the full-order closed-loop dynamics. This analysis is used to analyze stability margins and handling qualities.

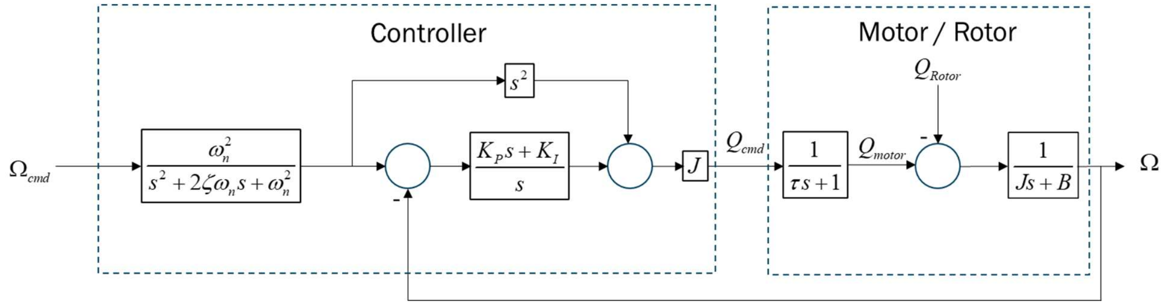

Figure 2 Model of Electric Motors and Motor Controller

3. CONTROLLER

The control design is based on linear Dynamic Inversion (DI), as presented in Ref. 7. Airspeed scheduling is used to account for the non-linear aircraft dynamics (i.e. variations in dynamics with flight condition) by interpolating the linear model A and B matrices with measured airspeed. The main modifications made in this study, relative to Ref. 7, were the integration of outer loop control modes that provide higher levels of augmentation both in hover / low-speed and transition / forward flight regimes. This study investigates the impact of these higher levels of augmentation on handling qualities and the effect of mode reversions to lower levels of control augmentation. Both the core inner loop control law and the selectable control modes will be described below.

3.1 Inner Loop Control Law

The core of the aircraft flight controller uses an airspeed scheduled DI control law, as documented in Refs. 7 and 8. Linear Dynamic Inversion uses state feedback and feedback linearization to approximately convert the aircraft dynamics into a system of de-coupled integrators. Simple SISO Proportional-Integral-Derivative (PID) compensators can then be used to stabilize the dynamics, reject disturbances, and account for modelling error in the reduced order linear models used in the control design.

The controller design is based on a reduced order 8-state linear models of the form:

$$\begin{aligned}
\dot{\mathbf{x}} &= \mathbf{Ax}+\mathbf{Bu} \\
\mathbf{y} &= \mathbf{Cx} \\
\mathbf{x}^T &= \begin{bmatrix} u & v & w & p & q & r & \phi & \theta \end{bmatrix} \\
\mathbf{y}^T &= \begin{bmatrix} \dot{\phi} & \dot{\theta} & V_z & r \end{bmatrix} \\
\mathbf{u}^T &= \begin{bmatrix} u_{lat} & u_{long} & u_{vert} & u_{dir} \end{bmatrix}
\end{aligned} \tag{2}$$

The state vector consists of rigid body states of the aircraft, the output vector consists of the Controlled Variables (CV), and the input vector are the inputs to the control mixing. Differentiating the output vector and then defining the input to achieve feedback linearization we have the following:

$$\begin{aligned}
\dot{\mathbf{y}} &= \mathbf{C}\dot{\mathbf{x}} = \mathbf{CAx}+\mathbf{CBu} \\
\mathbf{u} &= (\mathbf{CB})^{-1}(\mathbf{v}-\mathbf{CAx}) \\
&\Rightarrow \dot{\mathbf{y}} = \mathbf{v}
\end{aligned} \tag{3}$$

where

$$\mathbf{v}^T = \begin{bmatrix} v_\phi & v_\theta & v_{V_z} & v_r \end{bmatrix} \tag{4}$$

In theory, feedback linearization converts the plant into a system of decoupled integrators. Applying a linear compensator to the tracking errors of the controlled variables we can derive stable error dynamics as shown below. Since the system is decoupled, the following scalar equation gives the structure of the error dynamics for each control axis:

$$\begin{aligned}
v &= \dot{r}+K(s)e \\
e &= r-y \\
\dot{e} &+ K(s)e = 0
\end{aligned} \tag{5}$$

A schematic of this controls scheme is shown below in Figure 3.

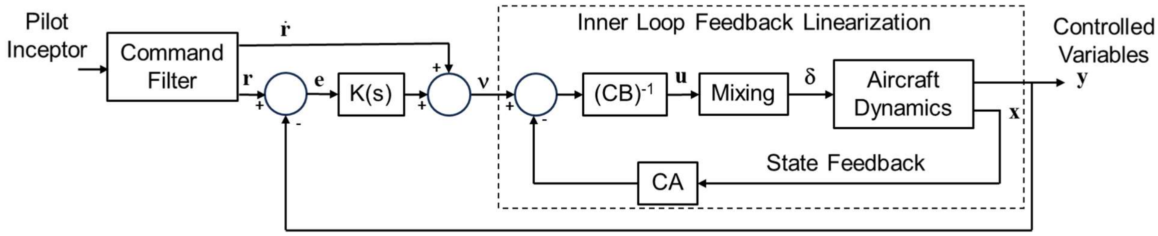

Figure 3 Schematic of Inner Loop Dynamic Inversion

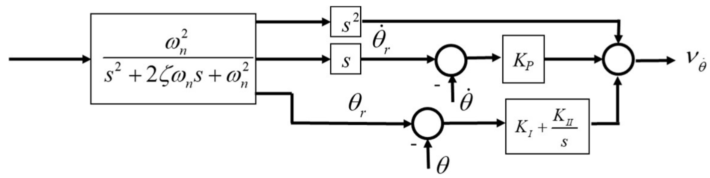

Figure 4 Schematic of the Pitch Axis ACAH Command Filter and Error Compensation

As discussed in Ref. 8, if external disturbances and modeling error are represented by disturbances on the plant output, the tracking error dynamics can be represented by the following transfer function:

$$\frac{e}{d}(s)=\frac{s}{s+K(s)} \tag{6}$$

If we apply proportional plus integrator plus double integrator compensator:

$$K(s)=K_p+\frac{K_I}{s}+\frac{K_{II}}{s^2}$$
$$\frac{e}{d}(s)=\frac{s^3}{s^3+K_p s^2+K_I s+K_{II}} \tag{7}$$

The characteristics polynomial can be factored so that gains are defined to specify the disturbance rejection dynamics via prescribed poles, typically a negative real pole and pair of damped complex poles.

$$\frac{e}{d}(s)=\frac{s^3}{(s+p)(s^2+2\zeta\omega_n s+\omega_n^2)} \tag{8}$$

In reality, the error dynamics will be higher order than the dynamics shown in Eq. 8, because much of the dynamics are neglected in the formulation (e.g. actuators, motors, inflow dynamics). Thus, once the error dynamics poles and corresponding gains are selected, linear analysis of the full order model is used to verify stability margins and handling qualities specifications.

In Figure 3, the reference input, $\mathbf{r}$, and its first derivative, $\dot{\mathbf{r}}$, are computed by a command filter to achieve desired response type and response bandwidth to pilot input. In VTOL mode, the inner loop control laws (referred to here as the "baseline" control law") achieve Attitude Command / Attitude Hold (ACAH) in the roll and pitch axes, vertical speed command / height hold in the vertical axis, and yaw rate command direction hold in the yaw axis. Once the aircraft converts to airplane mode, the lift rotors are stopped and can no longer be used for vertical axis control. In airplane mode, altitude control is achieved indirectly through pitch attitude. ACAH is still used in roll and pitch, while automatic turn coordination is used in yaw.

Note that the Controlled Variable (CV) for roll and pitch is listed as the first derivative of roll or pitch attitude in Equation 2, but the desired response type is Attitude Command (not Rate Command). The implementation of this is illustrated in Figure 4. A 2nd order command filter computers the reference signal for attitude rate (the CV), the attitude (integration of the CV), and the attitude acceleration (the derivative of the CV) as a feedforward term. Note that the proportional plus integrator plus double integrator compensation on attitude rate is equivalent to PID compensation on attitude.

Since this is a linear control design formulation, some implementation issues must be addressed when controlling the non-linear aircraft dynamics. The linear model provides an approximate representation of the aircraft perturbation dynamics around a trimmed operating point. The controller uses state feedback as would be estimated by an Inertial Navigation System (INS). The INS computes actual state estimates (not perturbation states), so the state feedback is passed through a high pass filter,

$G(s)=\frac{5s}{5s+1}$, to estimate perturbations from trim. The linear model matrices CA and $(CB)^{-1}$ are scheduled with measured airspeed to account for variations in the linearized dynamics across the flight envelope.

3.2 Pusher Propeller Controller

The pusher propeller is controlled either manually or via an airspeed command / airspeed hold autopilot. In manual control mode, the pilot uses a thumb switch on the collective inceptor to slew the propeller pitch up and down. When the speed controller is engaged, the pilot controls the airspeed either through the same switch or one of their inceptors (as will be discussed in the Unified Control modes below). When the airspeed command controller is engaged, the response type is Acceleration Command / Airspeed Hold. Figure 5 shows a schematic of this controller. The Airspeed Command control law is similar to that presented in Ref. 9. The controller is designed to blend seamlessly between manual propeller control and Airspeed Command, as both controllers drive the same integrator to slew up/down the propeller pitch. The gain K_{mode} transitions between 0 and 1 to switch between the manual mode and the airspeed controller. The speed controller uses PD compensation, which effectively becomes PI compensation when passed through the integrator.

3.3 Low Speed Outer Loop Control Law

The controller has a selectable Translational Rate Command / Position Hold (TRC/PH) control mode available when operating in hover and low speed. The basis of this TRC/PH controller was first presented in studies on flight control design for shipboard operations [10,11,12]. In this study, the TRC/PH mode has been updated for civil eVTOL applications with notable differences described below.

In Penn State's previous studies on Rotorcraft DI control, and in most rotorcraft flight control applications, the outer loop control of velocity and position generates attitude commands which are then fed into an inner loop control of attitude. These commands are passed into the attitude controller's command model in a series-type integration. This is illustrated in Figure 6 for the controller presented in Refs. 11 and 12.

A novel aspect of the TRC/PH controller is the use of 3rd order command filters (also known as reference models or command models) for the lateral and longitudinal axes that generate state commands at all integration levels of the equations of motion: velocity, acceleration, attitude, attitude rate, and attitude acceleration. These commands are fed directly into the tracking error compensation and dynamic inversion of the inner loop, bypassing the inner loop command filter in a parallel-type integration. Rather than using frequency separated command models for the velocity and attitude states, the single filter computes all state commands and feed forward signals for both translation and attitude in a numerically consistent filter.

Figure 7 shows the lateral (roll) axis TRC command filter. The pitch axis is nearly identical except for a negative sign on the gravity term that converts velocity derivatives to attitude signals. The command filter results in 3rd order linear response of the form:

$$\frac{V_{y_{cmd}}}{\delta_{lat}}(s)=\frac{Ka_0}{s^3+a_2s^2+a_1s+a_0} \tag{9}$$

This response model departs from the ADS-33 recommendations of a 1st order velocity response to pilot input. A third order command model is kinematically consistent with the true vehicle dynamics which requires coupling of 2nd order attitude + 1st order translation dynamics. As a result, the aircraft follows the command model more precisely.

As shown in Figure 8, the lateral TRC command filter produces commands in roll attitude, rate, and a feedforward command to angular acceleration. A series of Proportional (P) and Proportional-Integral (PI) feedback compensators are applied to compute roll pseudo-command, ν_ϕ. The pseudo-command is fed to the DI inner loop which de-couples the response of the various axes using feedback linearization as shown in Figure 3.

Figure 8 also provides a high-level illustration of how the TRC mode is integrated with the baseline ACAH controller. The same attitude feedback compensators and the same DI inner loop are used for both ACAH and TRC modes. It is not shown in the diagram, but there are also a series of initialization ports in both the ACAH and TRC command filters and the integrator compensators to ensure that mode switching to ACAH and TRC is smooth, i.e. does not result in a discrete jump in the actuator commands. This achieved by ensuring the initial attitude and actuator commands are synchronized between the two command filters and the compensators. There will still be transients due to changes in the command state when switching from TRC to ACAH, but transients will be smoothed by the command filter.

Some additional details of the controller not shown in the diagrams include: 1) Non-linear shaping that conforms with the recommended control sensitivities for TRC mode in MIL-DTL-32742, 2) Initial condition ports on the integrators for smoother engage / disengage, 3) A series of required coordinate transformations to convert inertial position and velocity values into a vehicle carried frame aligned with the aircraft heading (details of these kinds of transformations can be found in Ref. 13).

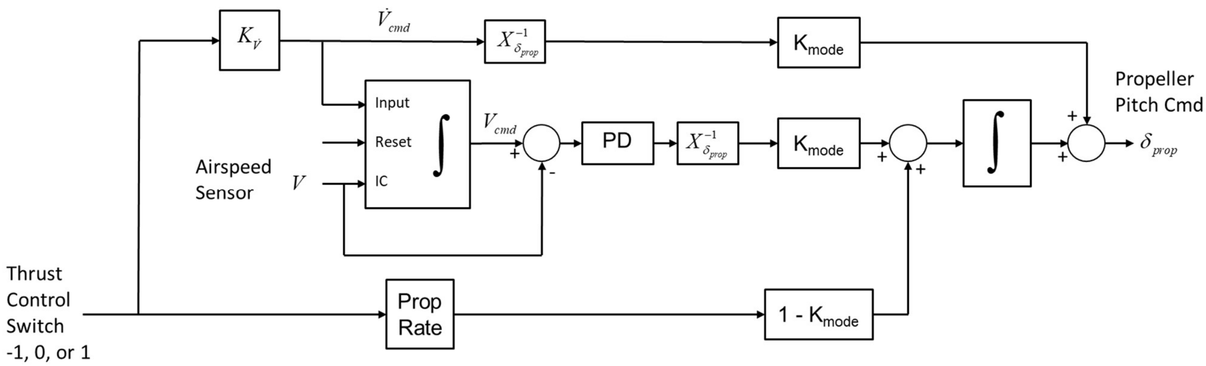

Figure 5 Pusher Propeller and Airspeed Command Controller

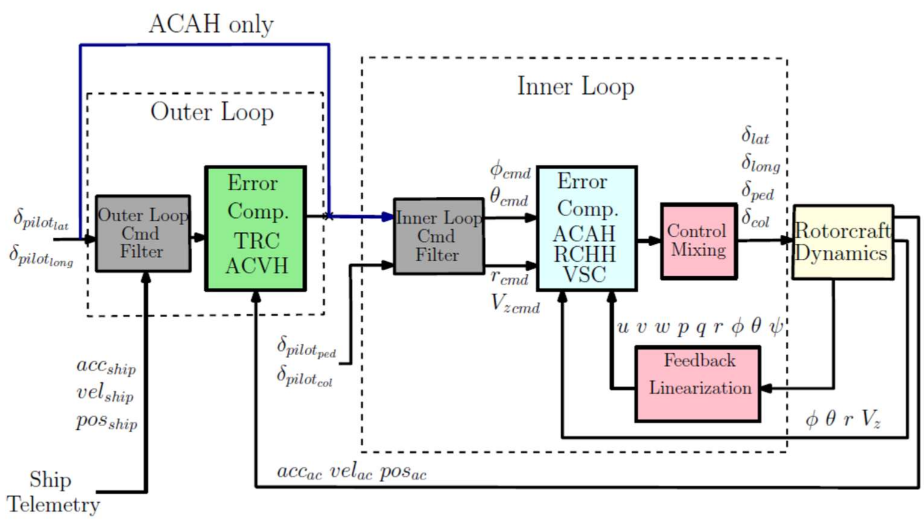

Figure 6 High Level Flight Control Architecture from Ref. 12.

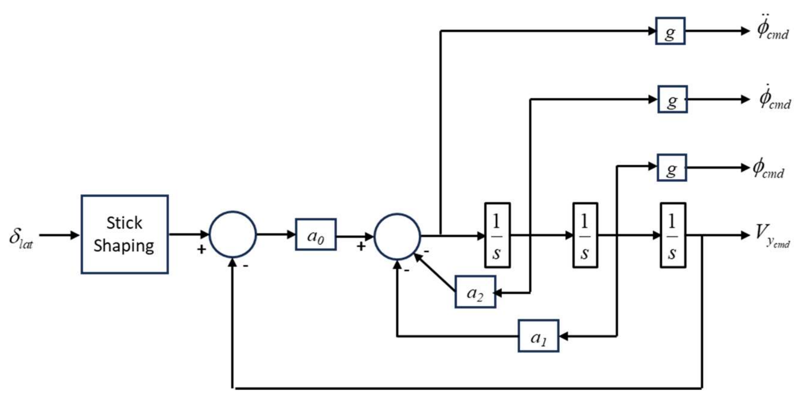

Figure 7 Schematic of Lateral TRC Command Filter

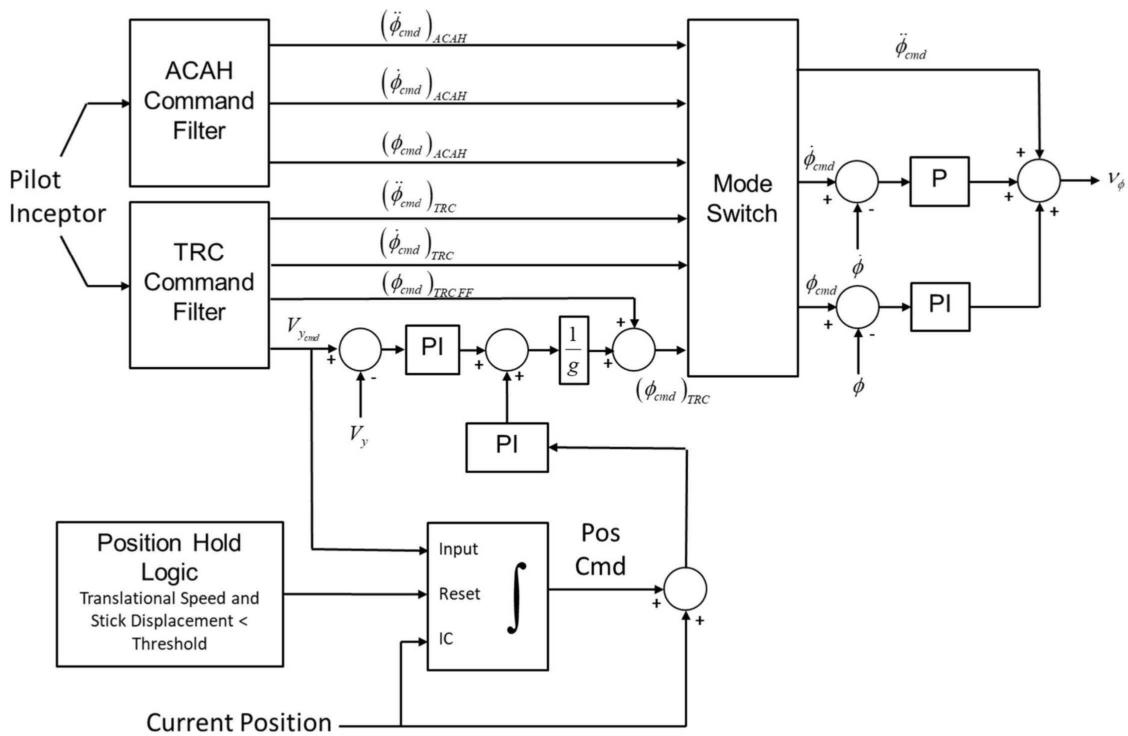

Figure 8 Schematic of Lateral Axis TRC / PH Control Law

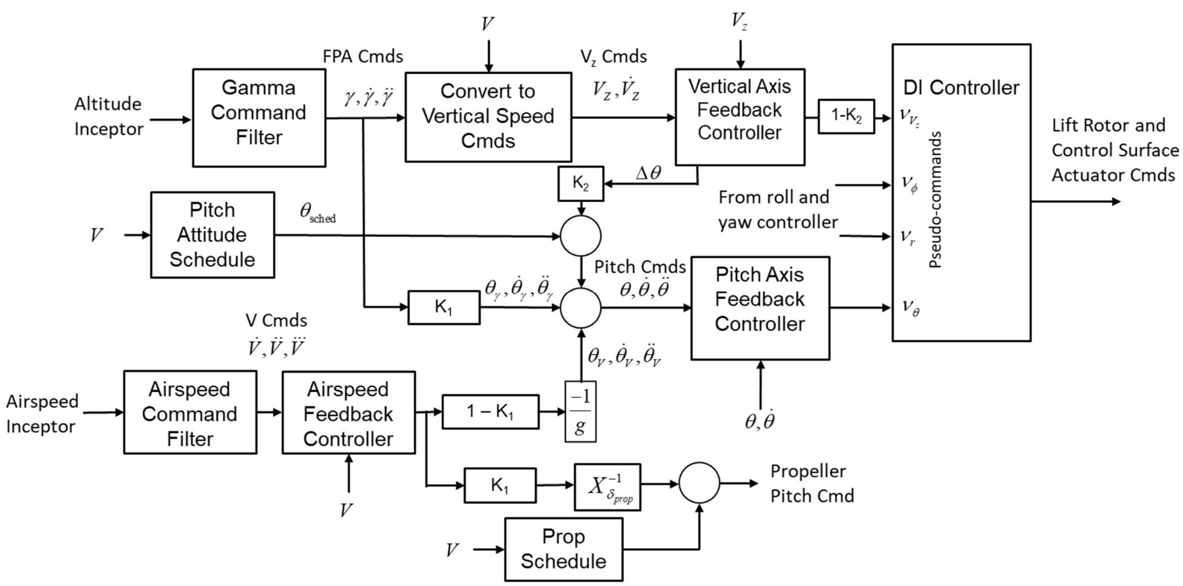

Figure 9 Unified Altitude and Airspeed Flight Control Law

3.4 Forward Flight Outer Loop Control law

In forward flight, the augmented flight control mode investigated in this study was designed to achieve decoupled altitude and airspeed control with Flight Path Angle Command / Altitude Hold and Acceleration Command / Airspeed Hold response types. The system is inspired by the Unified Flight Control developed initially under Vectored Thrust Aircraft Advanced flight Controls [VAAC] program and eventually used on the F-35B [14, 15]. Several studies have investigated the same response type for compound rotorcraft [16, 17] and this design draws heavily from those studies.

In unified flight control, one inceptor strictly controls altitude, by commanding vertical speed, Flight Path Angle (FPA), or FPA rate. A second inceptor strictly controls forward speed, for example using an Acceleration Command / Airspeed Hold response type. The most common unified implementation ties altitude control to the pilot's right-hand inceptor (a center stick or sidestick) while speed control is tied to the left-hand inceptor (throttle, collective, or Thrust Control Lever). However, the inceptors can be swapped with minor modification to the control law (simply swap inputs to the airspeed and altitude inceptor signals in Figure 9). In this study, both forms of unified control were investigated: right hand to altitude / left hand to speed, and right hand to speed / left hand to altitude. The latter scheme is more intuitive to helicopter pilots while the former is intuitive to fixed-wing pilots.

In addition to inceptor mapping, there can be variations in how the effectors are used to follow the commands. The lift rotors primarily affect vertical-axis forces, and the pusher propeller primarily affects longitudinal-axis forces. However, the pitch attitude of the aircraft (controlled via elevator and differential lift rotor thrust) can couple equally into both airspeed and altitude. In terms of outer loop flight control, the pitch attitude can be considered a type of control effector used for both speed and altitude control. In Ref. 17, a weighted pseudo-inverse control was used for allocation of main rotor collective, pusher propeller thrust, and pitch attitude in the unified control of a coaxial compound rotorcraft. The weighted pseudo-inverse was used to maximize control effectiveness while smoothly blending the use of the three effectors, where in high-speed pitch attitude is used for altitude control, while in low-speed pitch attitude is mainly used for speed control.

A similar approach was applied in this study. Figure 9 is a schematic of the unified flight control scheme. There are two mode switching gains K_1 and K_2, which blends the use of collective, pusher propeller thrust, and pitch attitude command. Rather than designing through pseudo-inverse the gain schedule was defined through simulation testing and pilot feedback, as will be discussed below. The final airspeed schedules for K_1 and K_2 are shown in Figure 10. In low-speed flight, V < 30 kts, $K_1 = K_2 = 0$, vertical axis control does not affect the pitch attitude command at all, and pitch attitude command is only used to achieve desire acceleration and to regulate forward speed. No propeller thrust is used and the propeller pitch is held at 0. In practice one might shut off the propeller in this regime, but this was not done in this test.

At higher transition speeds, V > 80 kts, $K_1 = 1$, feedforward signals are added to the pitch attitude command to track the commanded FPA, and airspeed control is controlled entirely with the propeller. At even higher airspeeds, V > 90 kts, $K_2 = 1$, the lift rotors are shut off, and there is no collective axis of control. At this point, both feedforward and feedback signals are sent to pitch attitude command to control and regulate altitude through the pitch axis. Note that all the simulation results presented in this paper were performed below 90 knots.

In the intermedia speed range, 30 to 80 knots, blended control performed, using both pitch attitude and propeller for airspeed control.

Note that in initial tests of the unified controller, the parameter K_1 was fixed at 0. Airspeed control was performed by the propeller only. The pitch attitude schedule would provide some nose up attitude as the aircraft decelerated, but the pitch was not tied into the airspeed control and regulation. Only in the final version of Unified (termed "Unified 3" in section 5 below), was the pitch attitude blended into airspeed regulation.

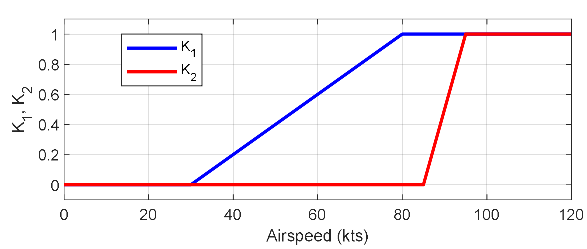

Figure 10 Mode Switching Gains in Unified Flight Control Law

3.5 Predicted Handling Qualities Analysis

Predicted handling qualities were analyzed using a subset of specifications in MIL-DTL-32742 and MIL-STD-1797B, and the stability margin requirements in SAE AS94900 (6 dB, 45°) as outlined in Table 2. All time-domain analyses were performed using non-linear simulations with prescribed inputs, while frequency domain analysis was performed using linear models extracted from the Simulink model of the full aircraft dynamics, the actuators, the motors, and the flight controller. Simulink's closed- and broken-loop linear model analysis tools were used to extract the models. For brevity, the details of the analyses are not included here, but Control parameters were tuned to meet Level 1 for all specifications listed in Table 2 wherever possible. There were two exceptions. The moderate amplitude response in roll and yaw were Level 2 in hover due to torque limiting on the motors.

Table 2 List of Specifications used in Design

SPECIFICATION	FLIGHT CONDITION	REQUIREMENTS
MIL-DTL-32742	Hover	3.2.1.5, 3.2.1.6, 3.2.1.8, 3.3.2, 3.3.3, 3.3.5, 3.3.6, 3.3.9.1, 3.3.11
MIL-DTL-32742	60 kts	3.4.1.1, 3.4.5.1, 3.4.6, 3.4.7.1
MIL-STD-1797B	100 kts	Roll, Pitch, Flight path bandwidth and phase delay
SAE AS94900	Hover,60 kts, 100 kts	Stability Margins

4. PILOTED SIMULATION TEST

4.1 Simulator

A piloted simulation study was conducted in the Penn State Rotorcraft Flight Simulation Facility as shown in Figure 11. The simulator features a 5-meter diameter spherical screen with a 6-channel high-resolution projection system offering up to 180° horizontal and 70° vertical fields of view. The simulation test was conducted with standard helicopter inceptors: a center cyclic stick, a lefthand collective lever, and pedals. A four-axis programmable Control Loading System defines the control forces on all axes.

The control inceptor force-feel characteristics are summarized in Table 3 below. These were tailored based on comments from pilots in a previous study [18] and further tuned by the evaluation pilot prior to the tests. The pilot suggested relatively light control forces. A trim release was available for the cyclic stick to re-trim the aircraft in the baseline ACAH mode. Trim release is generally not needed in the selectable modes, and trim release was not available in collective or pedals as it was not needed for these axes. Note that the collective axis has a breakout force but no gradient so that holding a sustained force on the collective is manageable by the pilot with a maximum force of 2 lbs.

Figure 11 PSU Rotorcraft Flight Simulation Facility

Table 3: Control Force Characteristics

Axis	*Travel*	*Gradient*	*Breakout*
Lateral Cyclic	10 in	0.56 lbs / in	1 lbs at ±0.1 in
Long. Cyclic	10 in	0.56 lbs / in	1 lbs at ±0.1 in
Coll.	10 in	None	2 lbs at ±0.2 in
Pedals	4 in.	13 lbs/in	5 lbs at ±0.06 in

The pilots had a standard primary flight display with attitude, airspeed, vertical speed indicator, barometric and radar altitude. For the heliport approach they also had a virtual Heads-Up Display (HUD) projected on the simulator visuals which included the same data as above and also a flight path vector.

4.2 Handling Qualities Task Elements

The piloted simulations were conducted with one experimental test pilot (XP) as well as several novice pilots (to evaluate potential of SVO with minimally trained pilots). The test included evaluations of five Handling Qualities Task Elements (HQTEs) developed by STI as proposed Means of Compliance for FAR Part 23 [3]. The HQTEs are similar to the MTEs defined in MIL-DTL-32742 but with modifications to performance bounds and cueing. The HQTEs included Precision Hover, Heliport Approach, Pitch and Roll Sum-of-Sines Tracking, Pirouette, and Lateral Reposition. In each simulation test, the XP provided Handling Qualities Ratings (HQR), Bedford Workload ratings (BWL), and Pilot Induced Oscillation Ratings (PIOR), and if appropriate ratings using the Integrated Failure Evaluation Scheme (IFES) [19]. The IFES requires the pilot to rate both the initial transient (IFES-T) and the recovery (IFES-R) following a flight control failure, with ratings from A to H, where A to D are minor, E is major, F and G hazardous, and H is catastrophic.

This paper will focus on the results of the Precision Hover and Heliport Approach. The Precision Hover course is shown in Figure 12. The heliport approach was performed along a 4.5-degree glide slope and the pilots used Precision Approach Path Indicator (PAPI) lights as a cue on the approach.

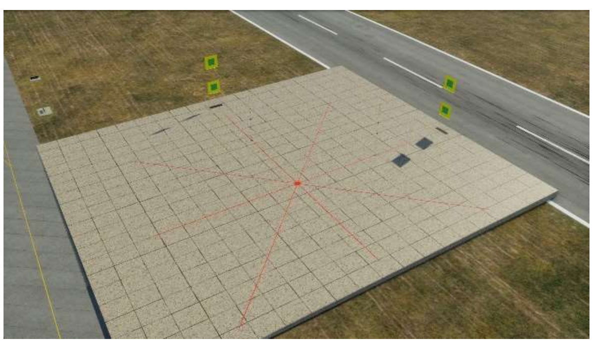

Figure 12 Hover MTE Course

4.3 Simulation based Automation and Failure Evaluations (SAFE) process

Systems Technology, Inc. has been working with NASA to develop a Simulation-based Automation and Failure Evaluations (SAFE) process to provide a reliable and repeatable certification means of compliance certification method for autonomous systems including degraded modes.

The SAFE process is intended to guide the user through the HQ evaluation process by constructing and dictating the test plan based on given requirements through a tablet-based application. The software efficiently collects and analyzes handling qualities data. This process was applied to integrate pilot comments, ratings, and quantitative data from the flight simulator, which was connected directly to the SAFE tablet, via UDP, for this study. In some cases, the rapid analysis of the simulation data afforded by the software enabled flight controller refinements to address handling qualities deficiencies as described below.

5. RESULTS

5.1 Precision Hover

The precision hover HQTE was flown in with 15 kts cross wind from the right side of the aircraft. The HQTE was performed in the baseline ACAH mode, in TRC/PH, and in TRC/PH which were reverted to ACAH mode during the approach phase of the HQTE. The winds were initiated after the start of the simulation requiring the pilot to bank into the wind to maintain hover when flying in ACAH mode. The pilot tried two different strategies: 1) Holding control force to maintain trim, 2) Using trim release to re-trim the stick prior to performing the HQTE. Re-trimming was the best strategy and resulted in Level 1 handling qualities, HQR 3, BWL 4, PIOR 1. Aircraft responses and pilot inputs for ACAH mode are shown in Figures 13-15. When holding control force, the handling qualities degraded to HQR 5, BWL 5, PIOR 2.

Figures 16-18 show similar results with TRC mode resulting in HQR 3, BWL 3, and PIOR 1. The improvement in BWL shows modest improvement over ACAH for this task. The results also show much less control activity than with ACAH mode, and the pilot is effectively “out of the loop” at the end of the task.

Figures 19 and 20 show response and pilot inputs during a failure case. A little over 20 seconds into the approach phase, the controller is switched to ACAH mode by the simulator operator (the pilot is not informed). In this case, the pilot is able to continue the task and assign HQR, BWL, as well as IFES ratings of the failure. The pilot noted that the failure caused the aircraft to accelerate. This is natural since the commanded attitude will exceed that required for the command speed in TRC mode, so the aircraft bank angle increases, and the aircraft accelerates. This readily observed by the pilot who then recovers the speed and able to capture hover a trim. However, workload is “considerable” (HQR 5) and there was some PIO tendency (PIOR 2). The excursion after failure was objectionable (IFES-T D) and recovery required considerable effort (IFES-R D). In the IFES scale these ratings are still considered “minor”. The pilot was able to achieve the desired performance in all categories except for the time to stabilize the hover. Note that it was not practical for the pilot to re-trim the stick in the middle of performing the HQTE, and the maneuver resulted in the same HQR as when flying the HQTE while flying with the baseline mode and holding control force.

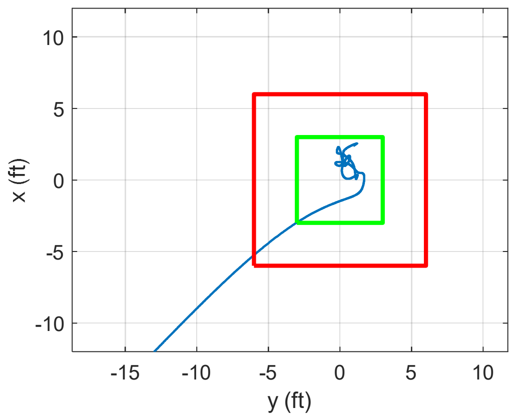

Figure 13 Precision Hover in 15 kts Crosswind, ACAH Mode with Stick Retrim, HQR 3, BWL 4

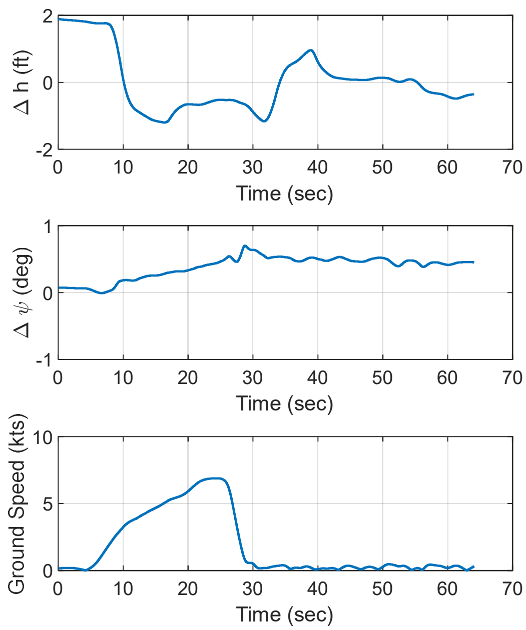

Figure 14 Altitude, Heading, Ground Speed, Precision Hover in 15 kts Crosswind, ACAH Mode with Stick Retrim, HQR 3, BWL 4

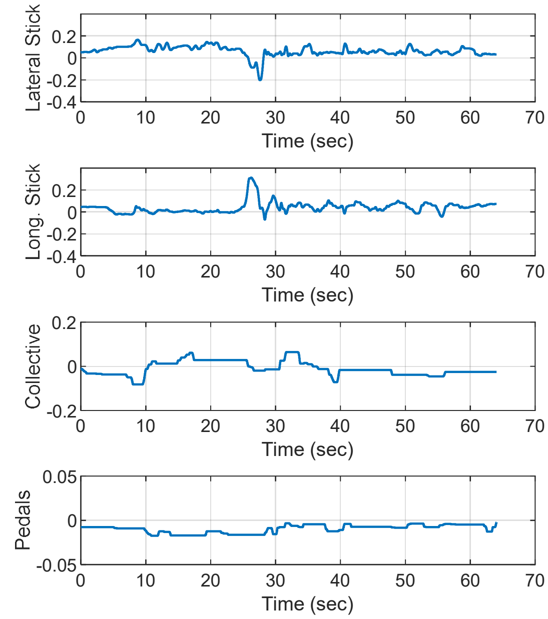

Figure 15 Pilot Inputs, Precision Hover in 15 kts Crosswind, ACAH Mode with Stick Retrim, HQR 3, BWL 4

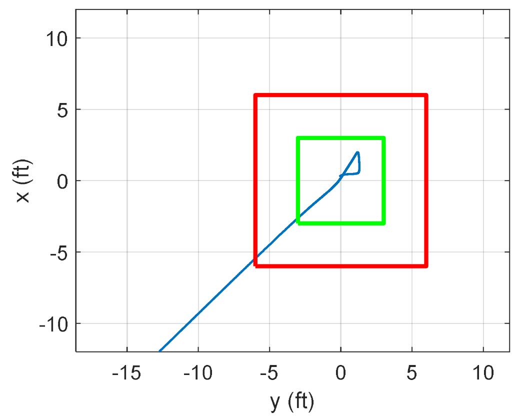

Figure 16 Position, Precision Hover in 15 kts Crosswind, TRC Mode, HQR 3, BWL 3

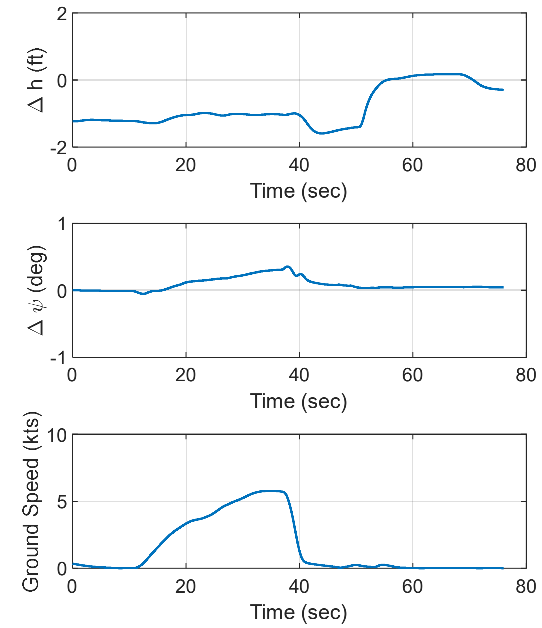

Figure 17 Altitude, Heading, Ground Speed, Precision Hover in 15 kts Crosswind, TRC Mode, HQR 3, BWL 3

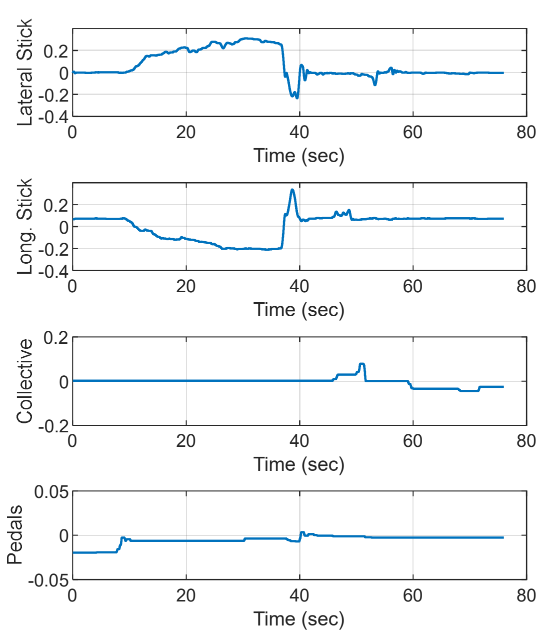

Figure 18 Pilot Inputs, Precision Hover in 15 kts Crosswind, TRC Mode, HQR 3, BWL 3

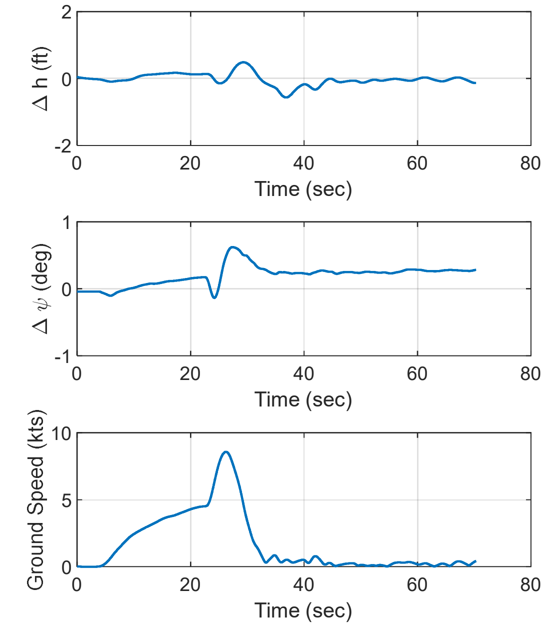

Figure 19 Altitude, Heading, Ground Speed, Precision Hover in 15 kts Crosswind, TRC Mode fails to baseline at 22.5 sec, HQR 5, BWL 5, PIOR 2, IFES-T D, IFES-R D

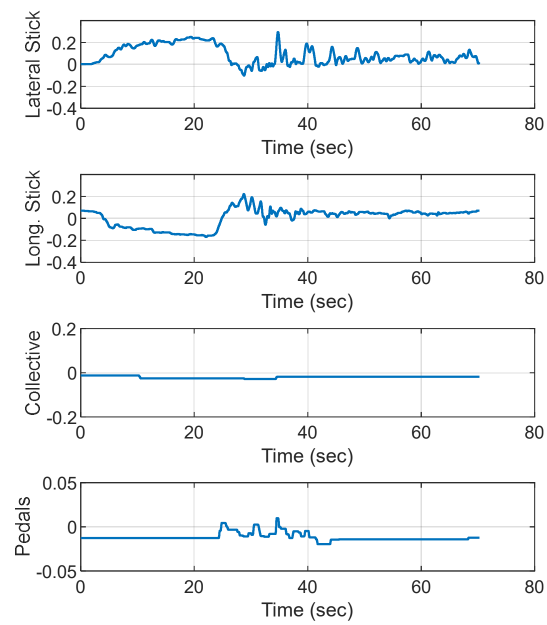

Figure 20 Pilot Inputs Precision Hover in 15 kts Crosswind, TRC Mode fails to baseline at 22.5 sec, HQR 5, BWL 5, PIOR 2, IFES-T D, IFES-R D

5.2 Heliport Approach

The heliport approach HQTE was performed in a 15 kts crosswind from the right side of the aircraft. Several controller configurations were flown, and ratings provided as summarized in Table 4. In the baseline control cases, the aircraft had ACAH response type in roll and pitch and vertical speed command in the collective axis. The pilot used the toggle switch on the collective to either manually control the propeller pitch, or to control the airspeed set point, which was displayed on their instruments and virtual HUD. There were three versions of the Unified flight controller as described below. Note that with the unified control the pilot does not need to use the toggle switch, they need only use their primary inceptors: cyclic stick, collective, and pedals.

- Unified 1: Collective inceptor was used for FPA command, longitudinal inceptor was used for acceleration command. Controller does not use pitch attitude in airspeed regulation.
- Unified 2: Longitudinal inceptor was used for FPA command, collective inceptor was used for acceleration command. Controller does not use pitch attitude in airspeed regulation.
- Unified 3: Longitudinal inceptor was used for FPA command, collective inceptor was used for acceleration command. Enhanced command blending between pitch attitude and propeller pitch for airspeed control.

Figures 21 to 25 show the simulation results for the Unified flight controllers.

The baseline control mode was flyable to adequate performance bounds with HQR 5. A general issue with the baseline modes was a tendency to overshoot the landing spot, as the pilot got behind in dialing back the propeller pitch. The addition of the airspeed controller reduced workload. The pilot noted that this added automation helped with off-axis control: “Where pilot did not have to integrate the pitch and prop thrust, they were able to manage track and lineup better.” However, this mode was still Level 2 at HQR 4.5.

The pilot preferred the Unified controllers in which collective controlled FPA and the longitudinal stick controlled acceleration (Unified 1 and Unified 3). The pilot noted that with Unified 2 they would “get behind cognitively” and sometimes mix up control actions between the two inceptors. This issue could be addressed with training. However, the pilot commented that if the pilot needs to be able to fly both the baseline and augmented modes, that is less adaptation required to switch between the modes if the collective inceptor remains an altitude controller.

The Unified 3 controller was the overall preference of the pilot and the only controller to achieve Level 1 HQ. In fact, this controller was largely designed around the pilot comments and feedback from the SAFE process. The main improvement was the more natural and smooth blending of pitch attitude in the longitudinal flight control in the terminal phase of the approach. As the pilot approaches the landing spot the pitch attitude increases proportional to stick and deceleration rate. This is seen in the steady rise in pitch attitude in Figure 24 over the last 15 seconds with the Unified 3 controller. The pilot noted that this is a useful cue to gauge their deceleration rate in the final part of the approach.

Table 4 Controller Configurations for Heliport Approach in Crosswind

Configuration	HQR	BWL	IFES
Baseline, ACAH and manual propeller	5	5	N/A
Baseline with Airspeed command controller	4.5	5	N/A
Unified 1	4	4	N/A
Unified 1 fail to baseline	5	5	IFES-T D IFES-R C
Unified 2	5, 7	6, 6	
Unified 2 fail to baseline	7	6	IFES-T A IFES-R D
Unified 3	3	4	N/A
Unified 3 fail to baseline	N/A	N/A	IFES-T C IFES-R C

Figures 26 and 27 show results for the Heliport Approach with a failure to the baseline controller. The switch occurs at about 57 seconds into the maneuver about 3600 ft downrange of the landing spot. Results are shown for Unified 2, where the longitudinal stick controls FPA, and Unified 3 where the collective stick control FPA. Note that in both configurations, the collective is lower than the detent as the pilot is both slowing down and decelerating. However, the longitudinal stick tends to be the opposite, it is forward for Unified 2 (to command descent) and aft for Unified 3 (to command deceleration). Upon failure, the controller switches to ACAH mode, causing a sharp nose up transient for Unified 3, while Unified 2 has a small transient, as the commanded pitch attitude roughly aligns with the FPA command. As a result, the transient failure rating, IFES-T, is better for Unified 2 (A versus D). On the other hand, after the transient the pilot needs to switch inceptor strategy, making recovery more difficult with Unified 2, IFES-R D versus IFES-R C for Unified 3. In addition, the pilot noted that the nose up transient with Unified 3 is in "the direction of safety", i.e. tends to make the aircraft climb. Therefore, even though the transient with Unified 3 was deemed a "moderate excursion" versus a "minimal excursion" with Unified 2, the Unified 3 controller was perceived as having superior failure characteristics.

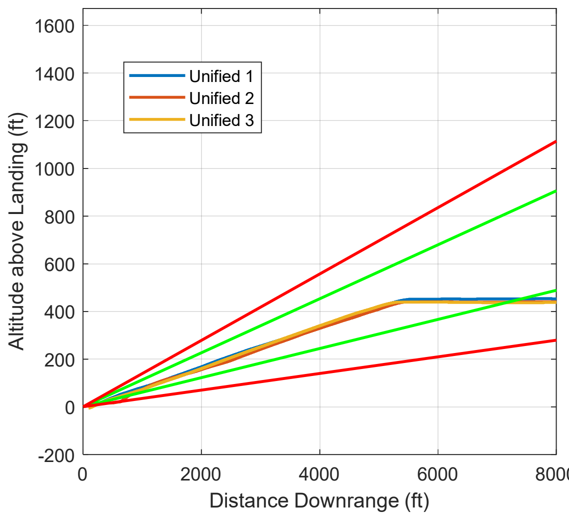

Figure 21 Vertical Flight Path on Heliport Approach

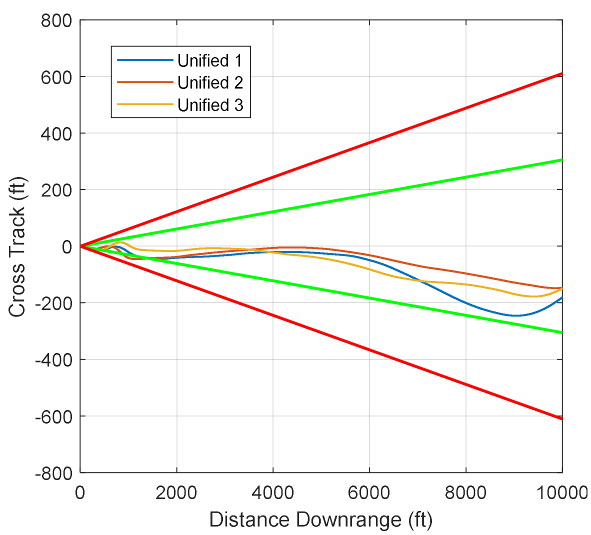

Figure 22 Horizontal Flight Path on Heliport Approach

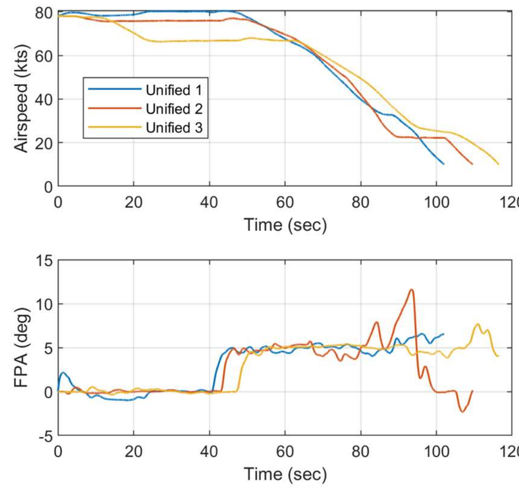

Figure 23 FPA and Airspeed on Heliport Approach

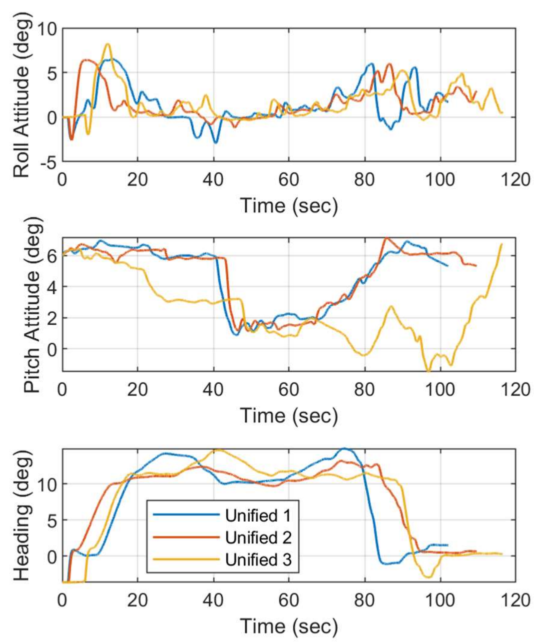

Figure 24 Aircraft Attitude on Heliport Approach

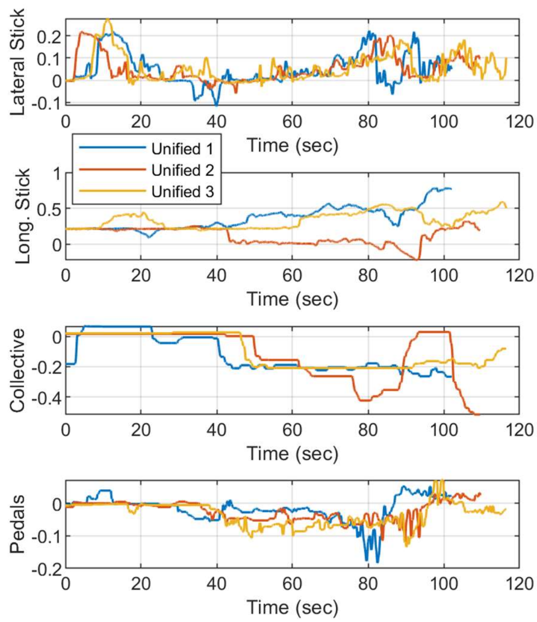

Figure 25 Pilot Stick Activity on Heliport Approach

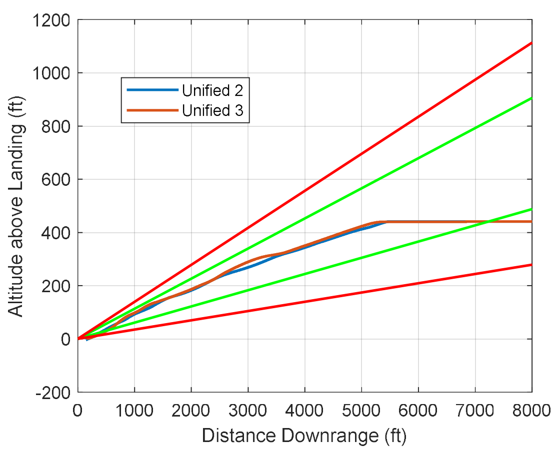

Figure 26 Vertical Flight Path on Heliport Approach, Failure to Baseline Mode at 3600 ft Downrange

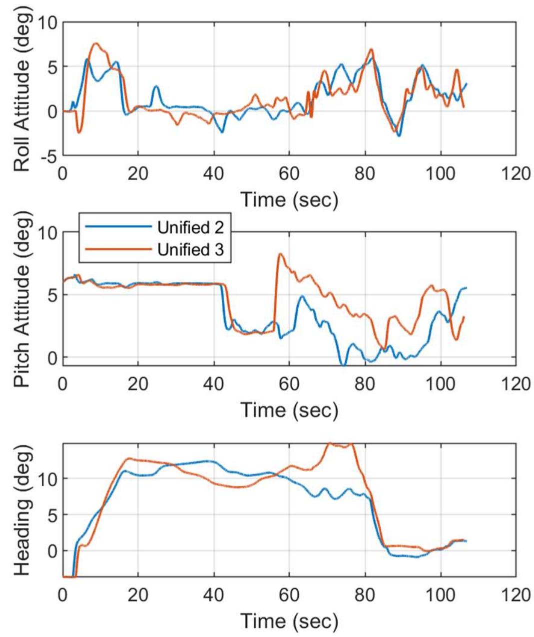

Figure 27 Aircraft Attitude on Heliport Approach, Failure to Baseline Mode at 57 seconds

6. CONCLUSIONS

This study conducted a piloted simulation investigation of control laws for an eVTOL aircraft, evaluating both nominal operations and mode reversions. The DI based flight controller featured an ACAH / Vertical Speed Command baseline controller, and selectable modes for TRC/PH response in low speed and Unified Flight Control for forward flight and approach.

Some specific conclusions from the study include the following.

1. The TRC/PH controller features a novel 3rd order command model and parallel integration with the inner loop control law. This was found to have good command tracking and Level 1 HQ for a Precision Hover in a cross wind. The controller had acceptable transient and recovery behavior and Level 2 HQ when reverting to the baseline control law.

2. A set of Unified Flight Controllers for airspeed and altitude control were evaluated in a Heliport Approach. The XP for this study preferred using the collective inceptor for altitude control and longitudinal inceptor for airspeed control, and this inceptor configuration resulted in improved HQ over the baseline controller. On the other hand, the conventional Unified arrangement, with longitudinal inceptor to altitude control, resulted in degraded HQ

relative to the baseline. The pilot noted that their preference for Unified Inceptor scheme might be driven by their past flying experience and training.

3. Modifications were made to the Unified Controller based on pilot commands and feedback from the SAFE process. The main modification was the integration of blended pitch attitude and propeller pitch to control airspeed in the low speed and transition regimes. The pilot noted that the pitch attitude changes during deceleration provides a useful cue on their deceleration rate during the terminal phase of the Heliport Approach. This configuration ("Unified 3") was the only configuration to achieve Level 1 Handling Qualities.

4. The Unified 3 configuration, which used the longitudinal cyclic for speed control, resulted in a larger nose up transient when reverting to the Baseline controller than the Unified 2 configuration, which used collective for speed control. However, the recovery was easier for the pilot, and the pilot noted that the nose up transient was "in the direction of safety", since it caused an altitude increase. Therefore, the mode reversion behavior was considered superior for Unified 3.

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