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Total Energy based Flight Control System Architecture for a Lift-Plus-Cruise Urban Air Mobility Aircraft

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Webcast for the
NASA Engineering and Safety Center Flight Mechanics Technical Discipline Team

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Ph.D., Aerospace Engineering (Dec 2015)
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Professional Memberships

- AIAA Associate Fellow (class of 2023)
- AIAA Aircraft Design Technical Committee
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Aviation

- Private Pilot, Airplane, Single-Engine, Land (Mar 2013 – present)
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Vehicle Systems, Dynamics, and Design Laboratory (VSDDL)

- VSDDL research focuses on sizing, performance and stability & control analysis, and flight simulation
- Developed the PEACE aircraft sizing framework, applicable to vehicles using wing-borne, rotor-borne, and buoyant lift or combinations thereof
- Developed the MADCASP S&C analysis and flight simulation framework with NASA funding; aimed at analysis of novel configurations
- Developed cockpit flight simulators to enable human-in-the-loop flight simulation research for Advanced Air Mobility (AAM) concepts

VSDDL

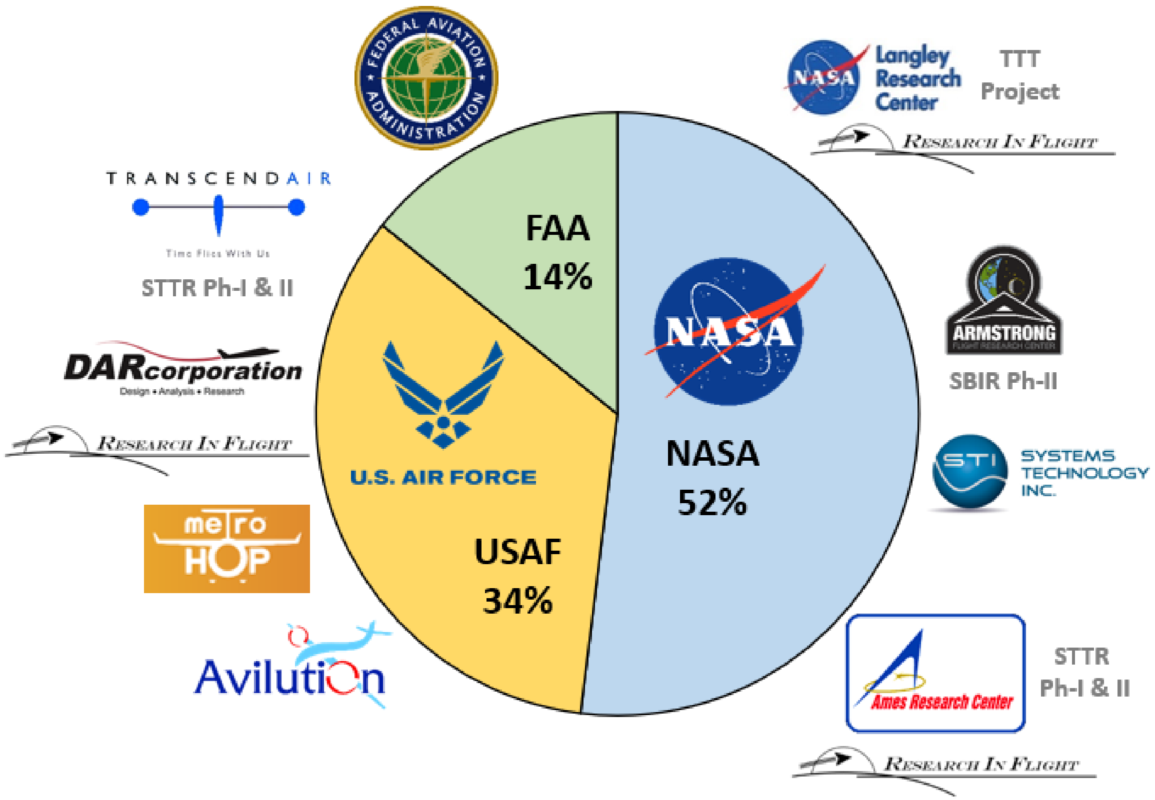
"Vehicle"
- Conventional & Unconventional

"Systems"
- Sizing & analysis of key systems

"Dynamics"
- Flight simulation, S&C analyses

"Design"
- Capture impacts of above on vehicle design

Cumulative external funding flowing to VSDDL @ AU from Aug 2018 – present: $1.5M+



VSDDL Vision: An R&D "Pipeline" for Next-Gen Concepts

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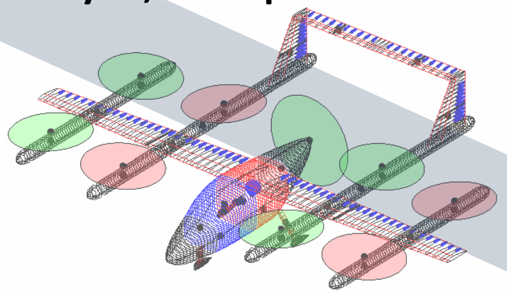
Vehicle sizing, performance analysis, and optimization

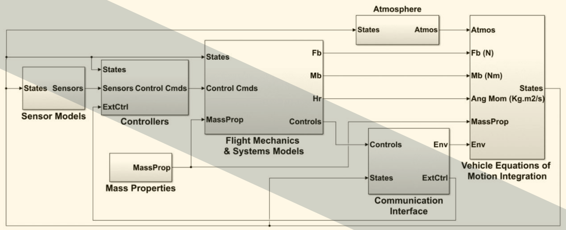


Parametric Energy-based Aircraft Configuration Evaluator (PEACE)

Developed internally at VSDDL; aimed at facilitating sizing and performance analysis of novel aircraft and propulsion system architectures

Webcast #1,
Feb 22, 2023, 1:00 pm EST

S&C analysis, flight control system architecture design & optimization

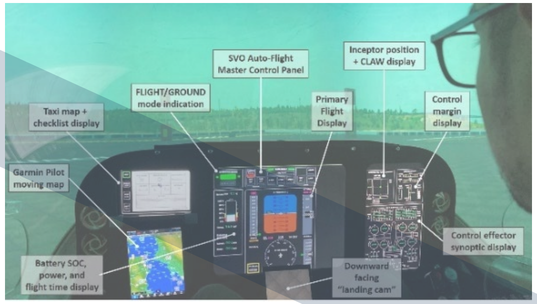


Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP)

Developed with funding from NASA Langley Research Center under Transformational Tools and Technologies (TTT) Project

Webcast #2,
Mar 1, 2023, 1:00 pm EST

Flight simulation model development; human-in-the-loop simulations

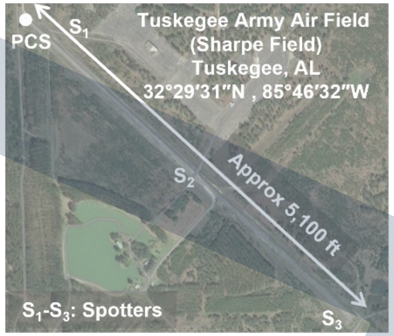


VSDDL Flight Simulators

Developed in-house for studying Simplified Vehicle Operations (SVO)

Webcast #3,
Mar 8, 2023, 1:00 pm EST

Subscale prototype development & piloted flight tests



VSDDL Vision: An R&D "Pipeline" for Next-Gen Concepts

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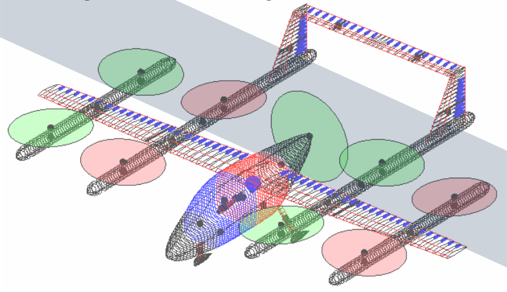
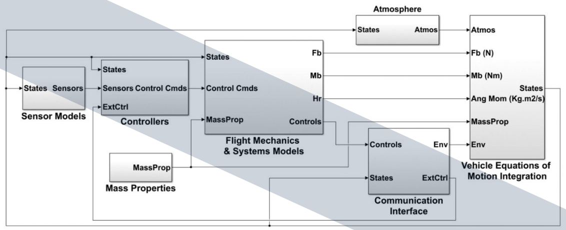
Vehicle sizing, performance analysis, and optimization



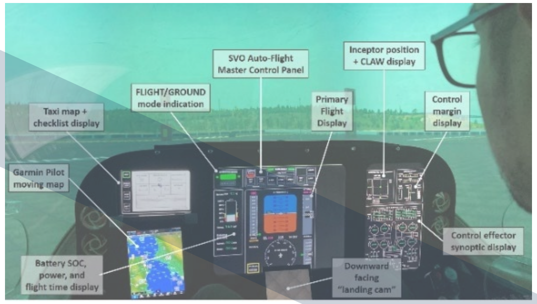
Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, [AIAA-2023-0398]

S&C analysis, flight control system architecture design & optimization



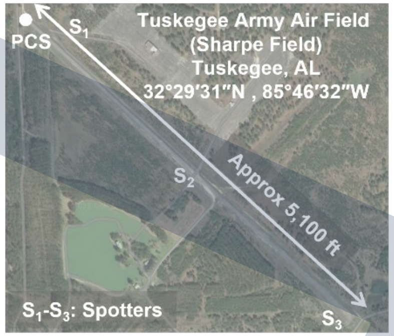
Comer, A. and Chakraborty, I., **"Total Energy Flight Control Architecture Optimization for a Lift-Plus-Cruise Aircraft,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, [AIAA-2023-0399]

Flight simulation model development; human-in-the-loop simulations



Chakraborty et al., **"Flight Simulation Based Assessment of Simplified Vehicle Operations for Urban Air Mobility,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, [AIAA-2023-0400]

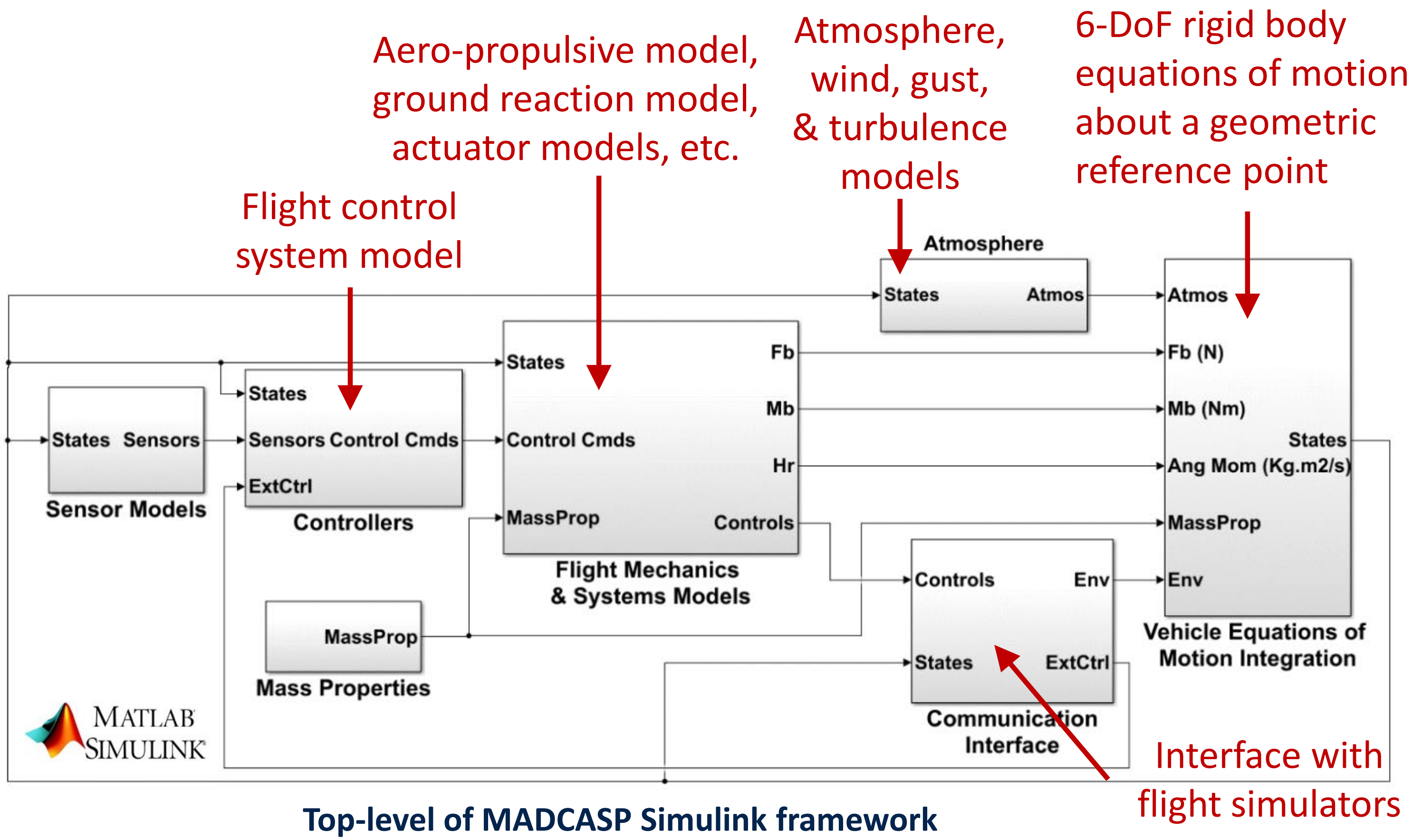
Subscale prototype development & piloted flight tests



MADCASP S&C Analysis and Flight Simulation Framework

- **Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP)**
  - MATLAB/Simulink-based S&C analysis and flight simulation framework
  - Developed with NASA LaRC funding under Transformational Tools and Technologies (TTT) project: *“Modular Generalized Framework for Assessing Aircraft Aero-Propulsive, Stability, and Control Characteristics”*, 80LARC19C0013 (Jan ’19 – Dec ’21)

- **Trim analysis:** Formulated as generalized constrained minimization problem
- **Dynamic stability analysis:**
  - Numerical linearization of model
  - eigenvalue problem on linearized models
- Integrates with **flight simulators**
  - Pilot-in-the-loop flight simulation (Webinar #3)
- Can input **PEACE** vehicle definition output
- Can use multiple forms of aero-propulsive performance models (APPM’s)



Top-level of MADCASP Simulink framework

MADCASP – Generalized Formulation of Trimming Problem

- **Trimming problem** is set up as a generalized **constrained minimization problem**

Find the values of these quantities…

$$TrimVector = \begin{bmatrix} \alpha \\ \beta \\ \phi \\ \dot{\psi} \\ \psi \\ (\gamma) \\ u_1 \\ u_2 \\ u_3 \\ . \\ . \end{bmatrix}$$

- α: Angle of attack
- β: Sideslip angle
- ϕ: Bank angle
- $\dot{\psi}$: Turn rate
- ψ: Heading
- (γ): Flightpath angle (if not specified)
- $u_1, u_2, u_3, \ldots$: Vehicle control variables (mapped to control effectors; multiple mappings possible)

To drive these residuals to zero

$$ResidualVector = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \\ K_{cust} \\ K_{track} \\ K_{turn} \\ K_{addl} \end{bmatrix}$$

- $\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}$: Translational and angular accelerations
- K_{cust}:
  - $= n_y$ (by default, for coordinated flight)
  - $= \psi - \psi_{set}$ (if heading specified)
  - $= \beta - \beta_{set}$ (if sideslip specified)
- $K_{track} = TRK - TRK_{set}$ (achieve the desired ground track)
- K_{turn}:
  - $= \phi - \phi_{set}$ (if bank angle specified
  - $= \dot{\psi} - \dot{\psi}_{set}$ (if turn rate specified)
  - $= n_{xz} - n_{xz_{set}}$ (if load factor specified)
  - $= R - R_{set}$ (if turn radius specified)
- K_{addl}: additional residuals for system states
  For example: propeller shaft-power balance

$$\frac{dN}{dt} = \frac{1}{I_{prop}}(\tau_{engine} - \tau_{prop})$$

I_{prop} … $= f(u_{throt}, h, \ldots)$; $\tau_{prop} = f(V_\infty, N, \beta_p)$

While minimizing a user-defined objective function

$$Objective\ Function = ??$$

Can penalize states and/or controls

Can be total propulsive power, etc.

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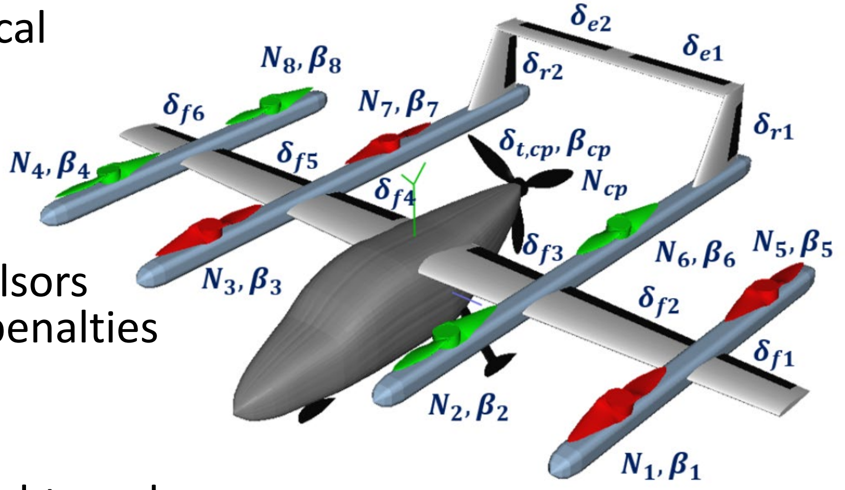
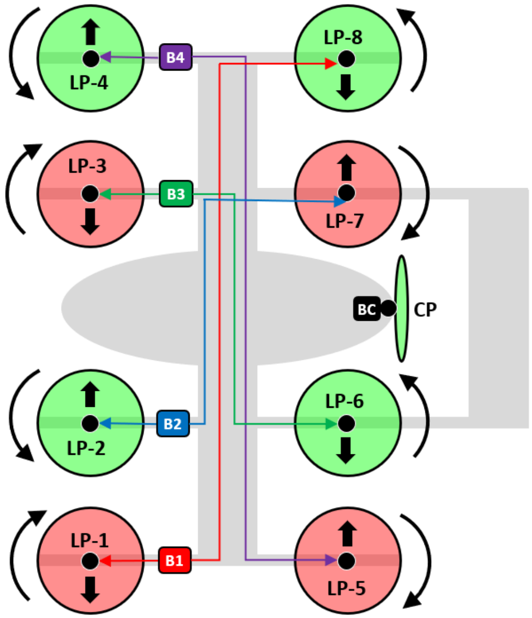
Lift-Plus-Cruise (LPC) Urban Air Mobility (UAM) Concept with Electrified Propulsion

- "Lift-Plus-Cruise" – separate propulsors for vertical thrust ("lift") and forward thrust (for cruise)
  - Advantage: Simpler aerodynamically than vectored thrust (tilt-wing and tilt-rotor)
  - Disadvantage: In cruise flight, the lift propulsors are inactive, thus "dead-weight" and drag penalties





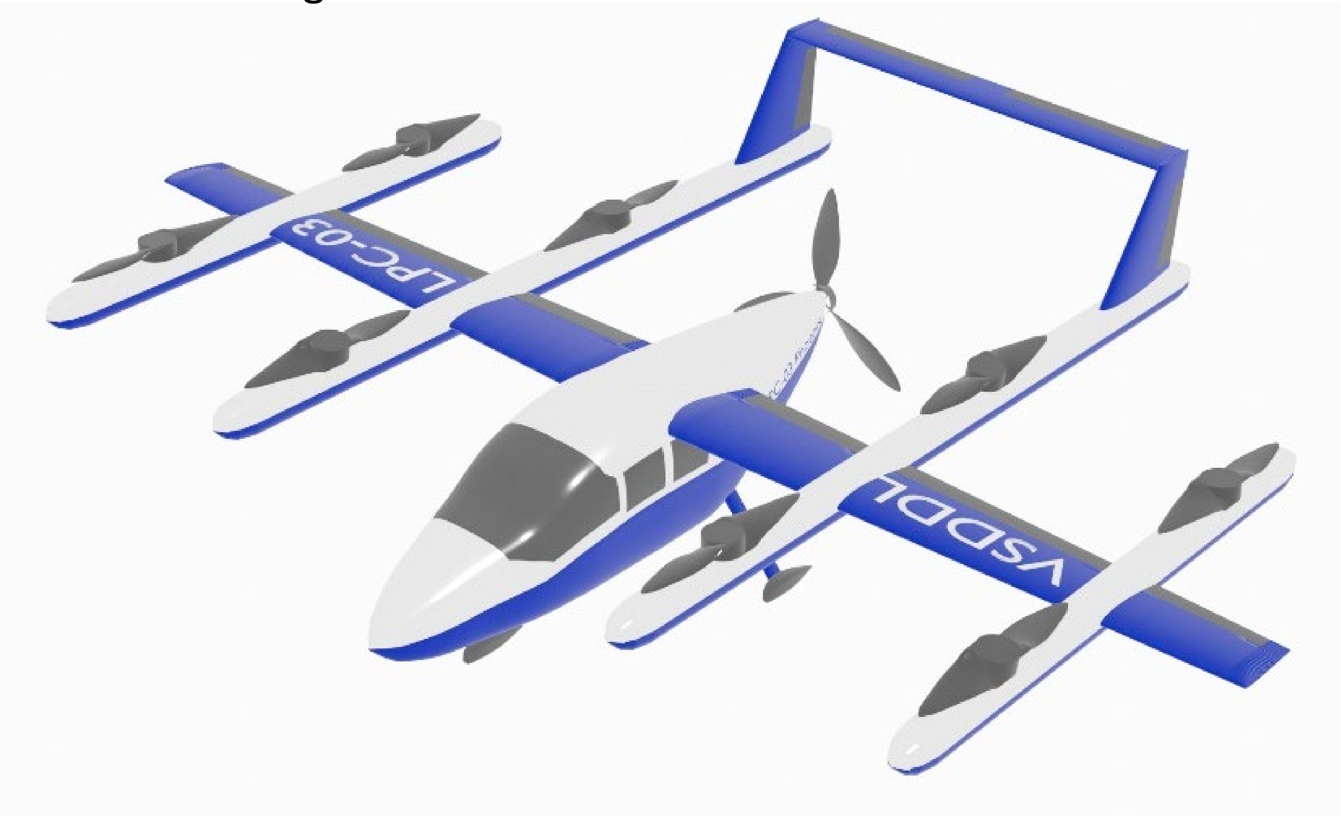
- **Forward flight mode:**
  - Conventional control surfaces in forward flight mode:
  - Flaperons (roll), elevators (pitch), rudders (yaw)

- **Vertical flight mode:**
  - **Roll control:** differential blade pitch between left- and right-side lift rotors
  - **Pitch control:** differential blade pitch between lift rotors ahead of and aft of wing
  - **Yaw control:** differential blade pitch between clockwise and anti-clockwise turning rotors (rotors are tilted inward/outward as indicated by arrows)

#	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 propeller throttle setting	–
12	β_{cp}	Cruise propeller pitch	deg
13	N_{cp}	Cruise propeller RPM	RPM
14-21	$N_1 - N_8$	Lift propeller RPMs	RPM
22-29	$\beta_1 - \beta_8$	Lift propeller pitch	deg

LPC-03 Sizing Summary

- LPC-03 Phoenix configuration was sized using the PEACE aircraft sizing framework



1. Chakraborty, I., and Mishra, A., **"Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion,"** AIAA Journal of Aircraft, 2022, https://arc.aiaa.org/doi/pdf/10.2514/1.C037044

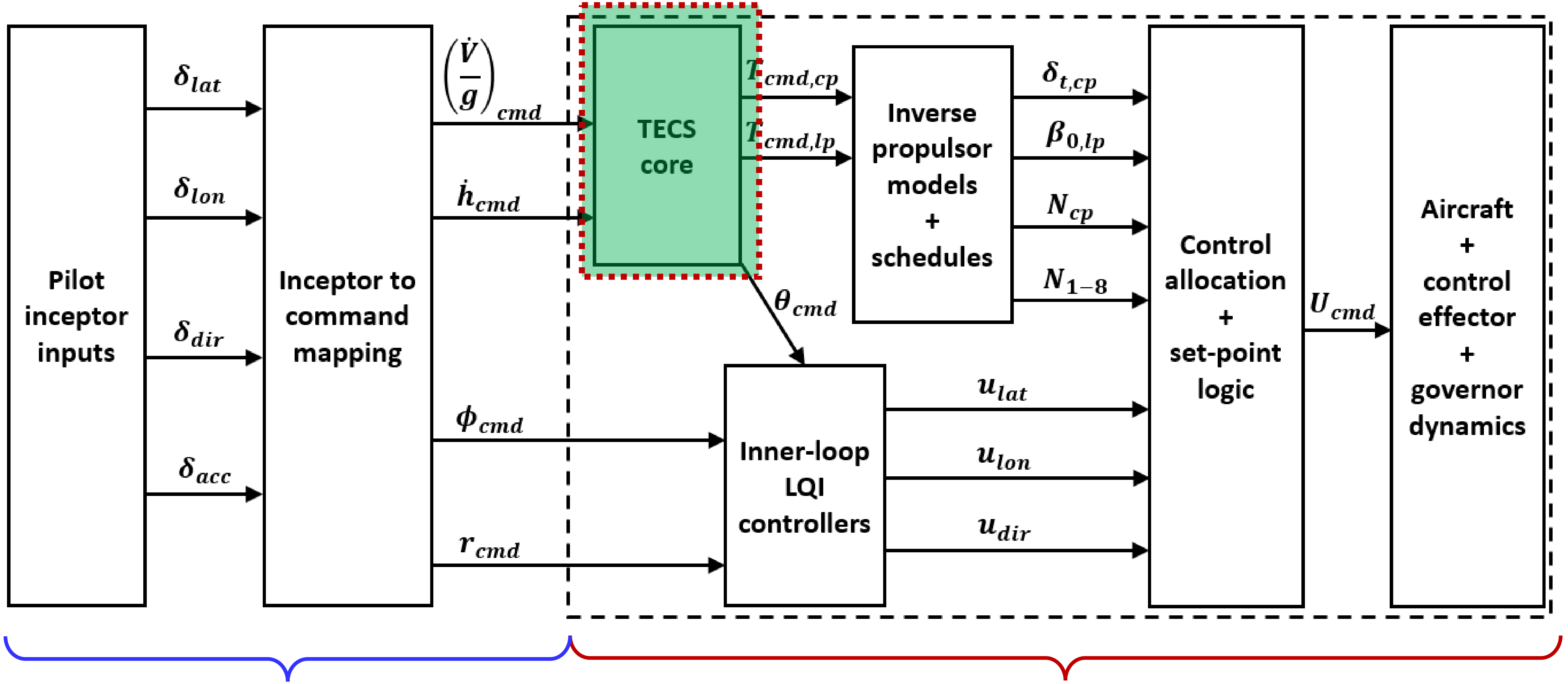
2. Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0398

3. NASA NESC Webinar, "Sizing and Optimization of a Lift-Plus-Cruise Urban Air Mobility Concept with Electrified Propulsion", Feb 22, 2023, https://go.nasa.gov/3EcgMpw

Parameter	Value	
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
Product of inertia (I_{xz})	-155.6 kg.m^2	3693 lb.ft^2
Main wing area	7.47 m^2	80.4 ft^2
Main wing span	9.47 m	31.1 ft
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
Lift propeller inertia	2.30 kg.m^2	54.6 lb.ft^2
Lift motor rated power (each)	8 x 92 kW	8 x 123 hp
Cruise propeller diameter	1.96 m	6.43 ft
Cruise propeller inertia	9.46 kg.m^2	224 lb.ft^2
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

LPC-03 all-electric sizing summary

Flight Control System Architecture for LPC-03



Focus of Webinar #3
https://go.nasa.gov/3KwFbKw

Focus of this Webinar
https://go.nasa.gov/3SoKBJm

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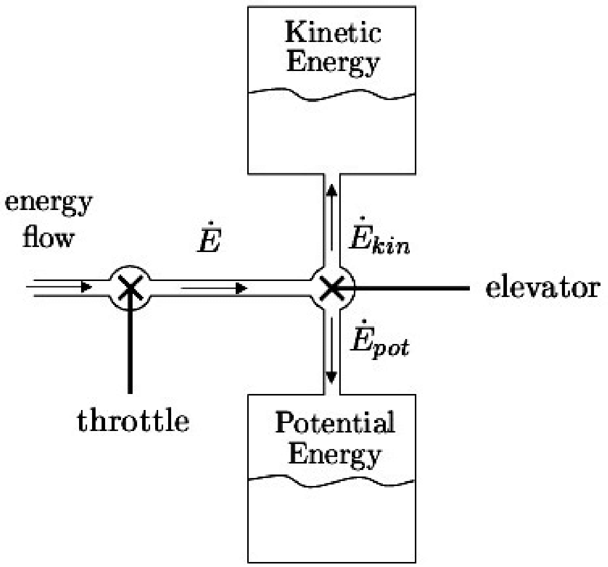
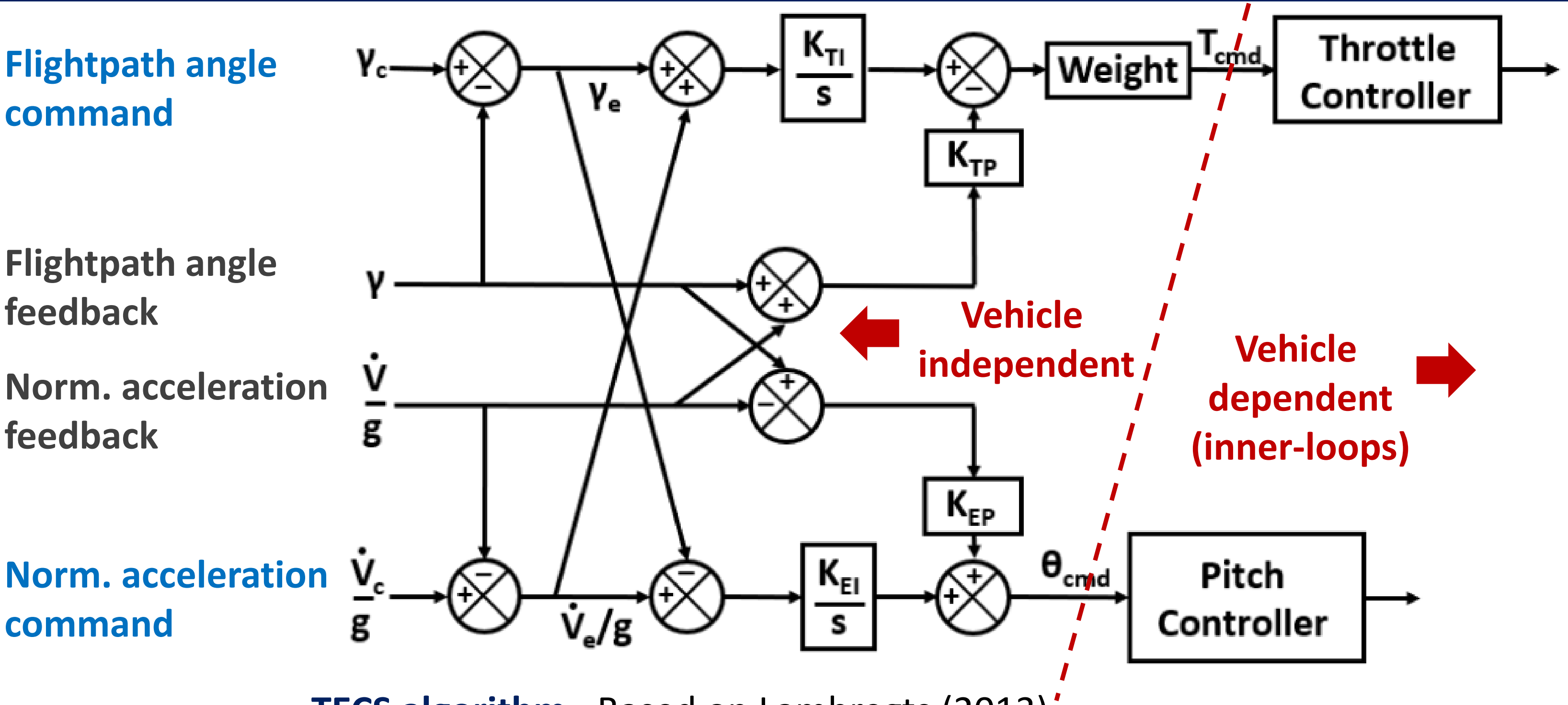
Total Energy Control System (TECS) Algorithm



The energy reservoir analogy
- Amelink et al. (2003)



TECS algorithm - Based on Lambregts (2013)

Specific total energy rate: $\dot{E} = \left(\frac{\dot{V}}{g}\right) + \gamma$

Its error: $\dot{E}_e = \dot{E}_{cmd} - \dot{E}$

Specific energy distribution rate: $\dot{L} = \left(\frac{\dot{V}}{g}\right) - \gamma$

Its error: $\dot{L}_e = \dot{L}_{cmd} - \dot{L}$

TECS Control Action

- Thrust Command: $\left(\frac{T}{W}\right)_{cmd} = \left(\frac{K_{T_I}}{s}\right)\dot{E}_e - K_{T_P}\dot{E}$
- Pitch Attitude Command: $\theta_{cmd} = -\left[\left(\frac{K_{E_I}}{s}\right)\dot{L}_e - K_{E_P}\dot{L}\right]$

Amelink et al., "Applying the Abstraction Hierarchy to the Aircraft Manual Control Task," Proc. of the 12th International Symposium on Aviation Psychology, Dayton, OH, USA, April 2003

Lambregts, A., "TECS Generalized Airplane Control System Design - An Update," Proceedings of the EuroGNC 2013, 2nd CEAS Specialist Conference on Guidance, Navigation and Control, FrAT3.1, Delft University of Technology, Delft, The Netherlands, April 10-12, 2013

Total Energy Control System (TECS) – Motivation & Past Applications

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- Traditional SISO control approach: flightpath control → auto-pilot, and airspeed control → auto-throttle system [1,2]
  - Does not explicitly account for the fact that the aircraft response to thrust and pitch control are coupled
  - Does not tactically coordinate the action of the flightpath and speed controllers
  - Crew confusion: Many control modes and sub-modes with functional overlap between A/P, A/T, and FMC
- Major TECS flight-test demonstrations
  - NASA Transport Systems Research Vehicle (TSRV) – a Boeing 737-100 aircraft [3]
  - CONDOR high-altitude long-endurance (HALE) unmanned aircraft [4]
  - Raytheon Beechcraft Bonanza general aviation aircraft [4]
- In addition to the above, several piloted simulation studies were conducted
- For a more detailed summary of past work involving TECS, see [5]

1. Faleiro, L., and Lambregts, A., "Analysis and tuning of a 'Total Energy Control System' control law using eigenstructure assignment," Aerospace Science and Technology, Vol. 3, No. 3, 1999, pp. 127–140
2. Lambregts, A., "TECS Generalized Airplane Control System Design - An Update," Proceedings of the EuroGNC 2013, 2nd CEAS Specialist Conference on Guidance, Navigation and Control, FrAT3.1, Delft University of Technology, Delft, The Netherlands, April 10-12, 2013
3. Bruce, K., Kelly, J., and Person, L., "NASA B737 Flight Test Results of the Total Energy Control System," AIAA Guidance, Navigation and Control Conference, Williamsburg, VA, 1986
4. Lambregts, A., "Generalized Automatic and Augmented Manual Flight Control," Berlin Technical University Colloquium, May 2006.
5. Comer, A. and Chakraborty, I., "Total Energy Flight Control Architecture Optimization for a Lift-Plus-Cruise Aircraft," AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0399

TECS Algorithm Modifications for LPC-03

- The classical TECS algorithm uses flightpath angle (FPA), γ, along with small angle approximations
  - For low-speed flight in vertical flight mode (VFM), FPA can be large and small angle approximation is invalid
  - For flight along vertical axis (vertical climb/descent), FPA $= \pm 90°$, i.e., not a useful feedback variable

- Define the quantity $F = \min\left(1, \frac{1}{|V|}\right)$
  - Replace γ_{cmd} with $F\,\dot{h}_{cmd}$ in TECS implementation
  - And replace γ with $F\dot{h}$
  - The modified TECS algorithm operates on vertical velocity (always well-defined), as opposed to FPA

- At higher speeds, note that $F = \frac{1}{V}$
  - This means that $F\,\dot{h}_{cmd} = \frac{1}{V}\dot{h}_{cmd} = \sin\gamma_{cmd} \approx \gamma_{cmd}$ and $F\dot{h} = \frac{1}{V}\dot{h} = sin\gamma \approx \gamma$
  - The modified TECS algorithm will then behave like the classical scheme that operates on FPA

- At hover or very low speeds, note that $F = 1$
  - This means that $F\,\dot{h}_{cmd} = \dot{h}_{cmd}$ and $F\dot{h} = \dot{h}$
  - The modified TECS algorithm operates on vertical velocity directly

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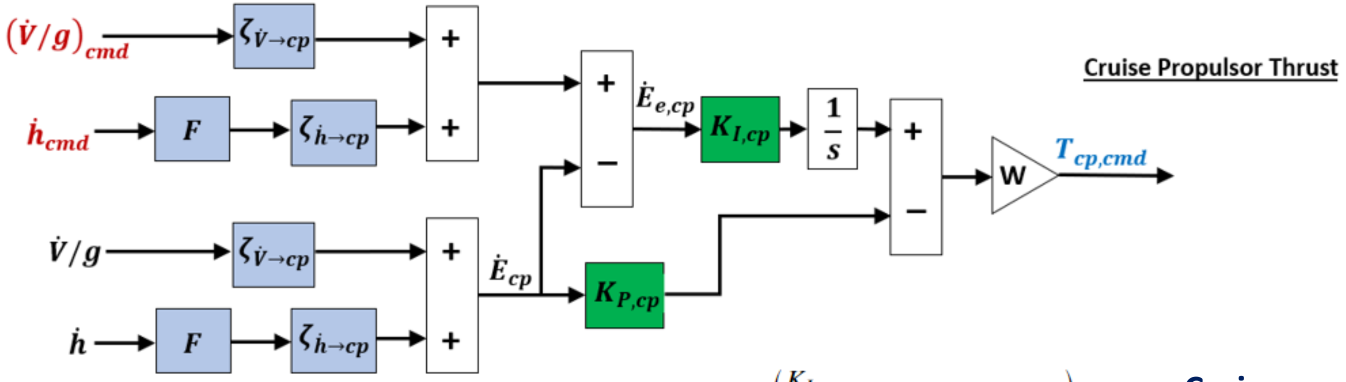
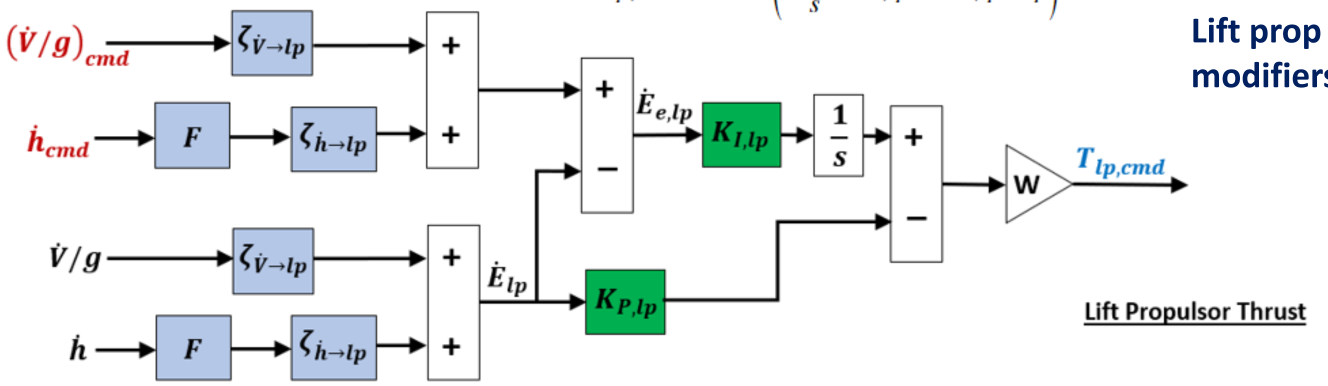
TECS Algorithm Modifications for LPC-03 (continued)

- The classical TECS algorithm has **two** outputs: a thrust command and a pitch attitude command
- The TECS implementation for LPC-03 has **three** outputs:
  (i) cruise prop thrust $T_{cmd,cp}$, (ii) lift prop thrust $T_{cmd,lp}$, (iii) pitch attitude command θ_{cmd}



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

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

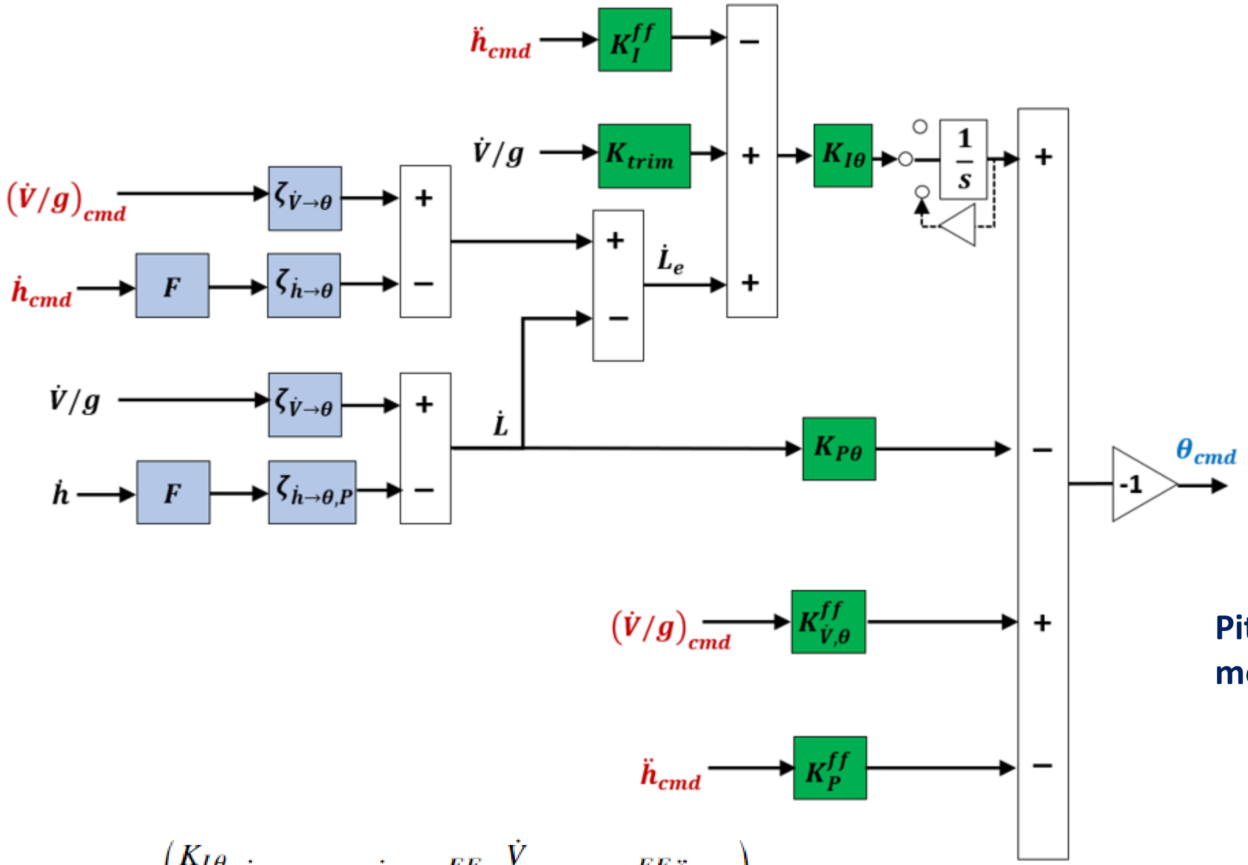


Commands	Feedback	Outputs	Gains	Modifiers
$(\dot{V}/g)_{cmd}$	$\dot{V}/g$	$T_{cp,cmd}$	$K_{I,cp}$	F
$\dot{h}_{cmd}$	$\dot{h}$	$T_{lp,cmd}$	$K_{P,cp}$	$\zeta_{\dot{V}\to cp}$
	V		$K_{I,lp}$	$\zeta_{\dot{h}\to cp}$
			$K_{P,lp}$	$\zeta_{\dot{V}\to lp}$
				$\zeta_{\dot{h}\to lp}$

	KEAS	0	40	45	80	120	135	140	160	200+
Cruise prop modifiers	$\zeta_{\dot{h}\to cp}$	0	0	0	0	0	0	1	1	1
	$\zeta_{\dot{V}\to cp}$	0	0	1	1	1	1	1	1	1
Lift prop modifiers	$\zeta_{\dot{h}\to lp}$	1	1	1	1	1	1	0	0	0
	$\zeta_{\dot{V}\to lp}$	1	1	0	0	0	0	0	0	0
	$\zeta_{\dot{h}\to\theta}$	0	0	0	0	0	0.75	1	1	1
	$\zeta_{\dot{h}\to\theta,P}$	0	0	0	0	0	0.75	1	1	1
	$\zeta_{\dot{V}\to\theta}$	1	1	0	0	0	0	0	0	0

TECS Algorithm Modifications for LPC-03 (continued)

- The classical TECS algorithm has **two** outputs: a thrust command and a pitch attitude command
- The TECS implementation for LPC-03 has **three** outputs:
  (i) cruise prop thrust $T_{cmd,cp}$, (ii) lift prop thrust $T_{cmd,lp}$, (iii) pitch attitude command θ_{cmd}



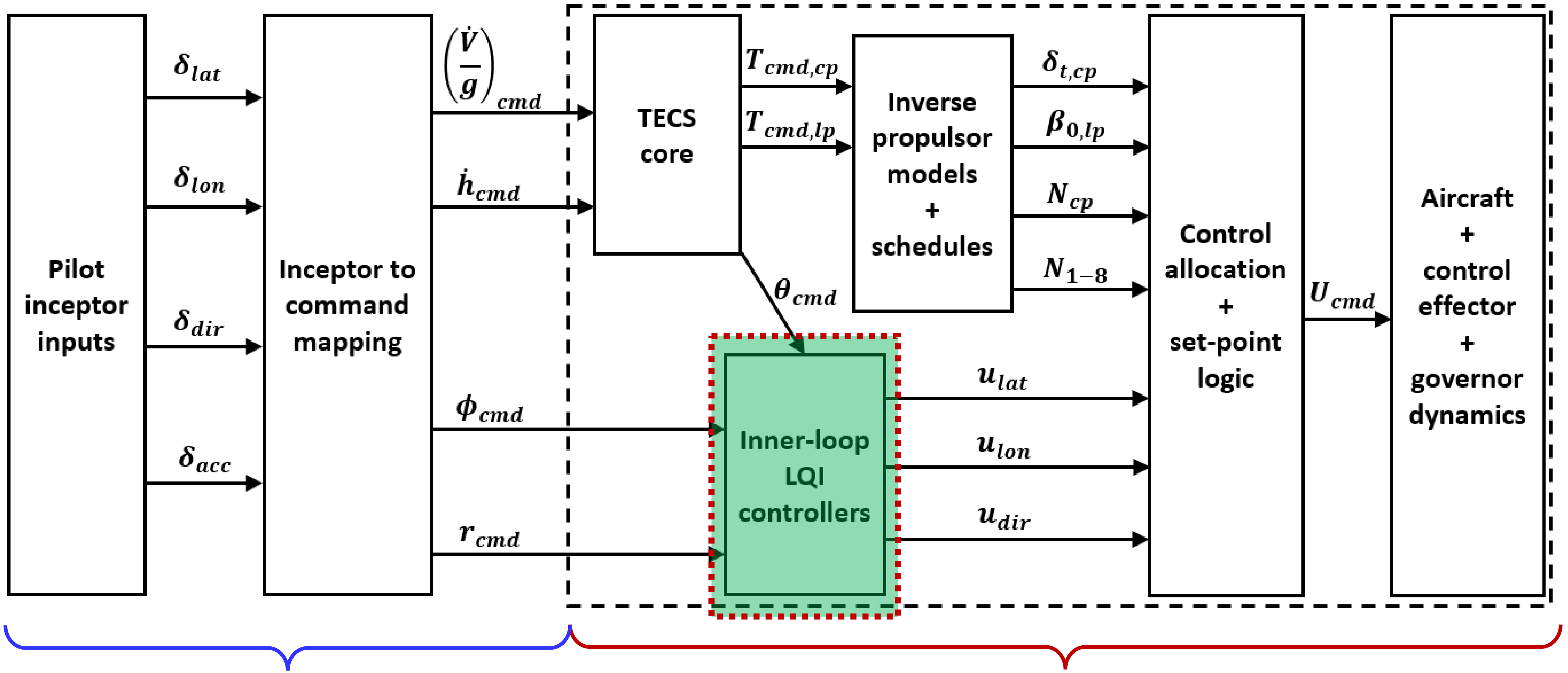
$$\theta_{cmd} = -\left(\frac{K_{I\theta}}{s}\dot{L}_e - K_{P\theta}\dot{L} + K^{FF}_{\dot{V}\to\theta}\frac{\dot{V}}{g}_{cmd} - K^{FF}_{P}\ddot{h}_{cmd}\right)$$

Commands	Feedback	Output	Gains	Modifiers
$(\dot{V}/g)_{cmd}$	$\dot{V}/g$	θ_{cmd}	$K_{I\theta}$	F
$\dot{h}_{cmd}$	$\dot{h}$		$K_{P\theta}$	$\zeta_{\dot{V}\to\theta}$
$\ddot{h}_{cmd}$	V		K_{trim}	$\zeta_{\dot{h}\to\theta}$
			K_I^{ff}	$\zeta_{\dot{h}\to\theta,P}$
			K_P^{ff}	
			$K^{ff}_{\dot{V},\theta}$	

KEAS	0	40	45	80	120	135	140	160	200+
$\zeta_{\dot{h}\to cp}$	0	0	0	0	0	0	1	1	1
$\zeta_{\dot{V}\to cp}$	0	0	1	1	1	1	1	1	1
$\zeta_{\dot{h}\to lp}$	1	1	1	1	1	1	0	0	0
$\zeta_{\dot{V}\to lp}$	1	1	0	0	0	0	0	0	0
$\zeta_{\dot{h}\to\theta}$	0	0	0	0	0	0.75	1	1	1
$\zeta_{\dot{h}\to\theta,P}$	0	0	0	0	0	0.75	1	1	1
$\zeta_{\dot{V}\to\theta}$	1	1	0	0	0	0	0	0	0

Pitch modifiers: $\zeta_{\dot{h}\to\theta}$, $\zeta_{\dot{h}\to\theta,P}$, $\zeta_{\dot{V}\to\theta}$

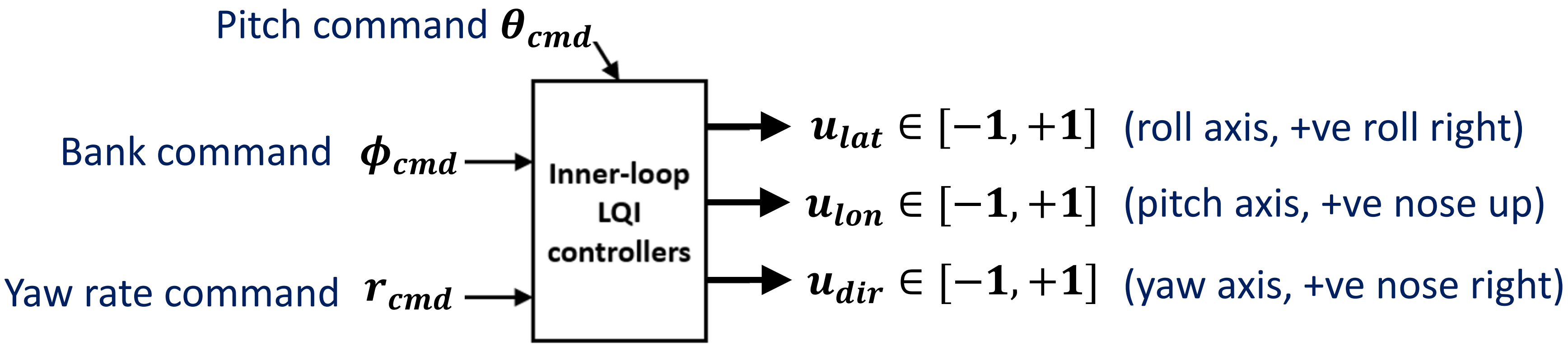
Flight Control System Architecture for LPC-03



Focus of Webinar #3
https://go.nasa.gov/3KwFbKw

Focus of this Webinar
https://go.nasa.gov/3SoKBJm

Inner-Loop LQI Controllers



LQI:
Linear Quadratic Regulators with Integral Action

Definition of error quantities:

$$e_\theta = \theta_{cmd} - \theta, e_\phi = \phi_{cmd} - \phi, e_r = r_{cmd} - r$$

Longitudinal inner-loop control

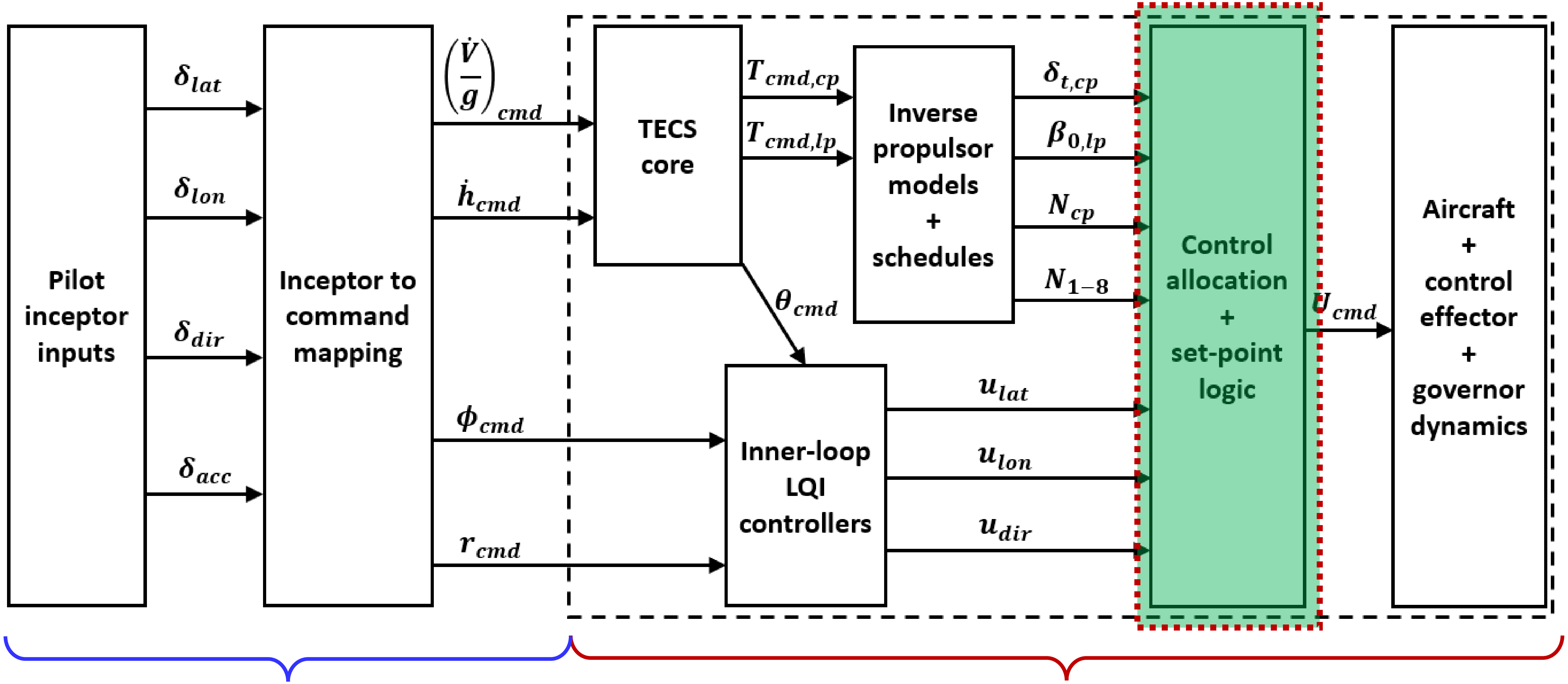
$$u_{lon} = -K_{long}^{1\times4} \left[w \quad q \quad \theta \quad \int e_\theta \, dt \right]^T$$

Lateral-directional inner-loop control

$$\left[u_{lat} \quad u_{dir} \right]^T = -K_{lat}^{2\times5} \left[p \quad r \quad \phi \quad \int e_\phi \, dt \quad \int e_r \, dt \right]^T$$

The gains within gain matrices $K_{long}^{1\times4}$ and $K_{lat}^{2\times5}$ are determined during optimization

Flight Control System Architecture for LPC-03



Focus of Webinar #3
https://go.nasa.gov/3KwFbKw

Focus of this Webinar
https://go.nasa.gov/3SoKBJm

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Control Allocation

- Flaperons: $\delta_{f1}, \delta_{f2}, \delta_{f3} = \delta_f^{max} u_{lat}, \quad \delta_{f4}, \delta_{f5}, \delta_{f6} = -\delta_f^{max} u_{lat},$
- Elevators: $\delta_{e1}, \delta_{e2} = -\delta_e^{max} u_{lon},$
- Rudders: $\delta_{r1}, \delta_{r2} = \delta_r^{max} u_{dir}$
- Lift propulsor blade pitch:

$$\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \\ \beta_6 \\ \beta_7 \\ \beta_8 \end{bmatrix} = \begin{bmatrix} 1.00 & 1.00 & 0.43 & -0.54 \\ 1.00 & 0.54 & 1.00 & 1.00 \\ 1.00 & -0.54 & 1.00 & -1.00 \\ 1.00 & -1.00 & 0.43 & 0.54 \\ 1.00 & 1.00 & -0.43 & -0.54 \\ 1.00 & 0.54 & -1.00 & 1.00 \\ 1.00 & -0.54 & -1.00 & -1.00 \\ 1.00 & -1.00 & -0.43 & 0.54 \end{bmatrix} \begin{bmatrix} \beta_{0,lp} \\ \beta_\phi \\ \beta_\theta \\ \beta_\psi \end{bmatrix}$$

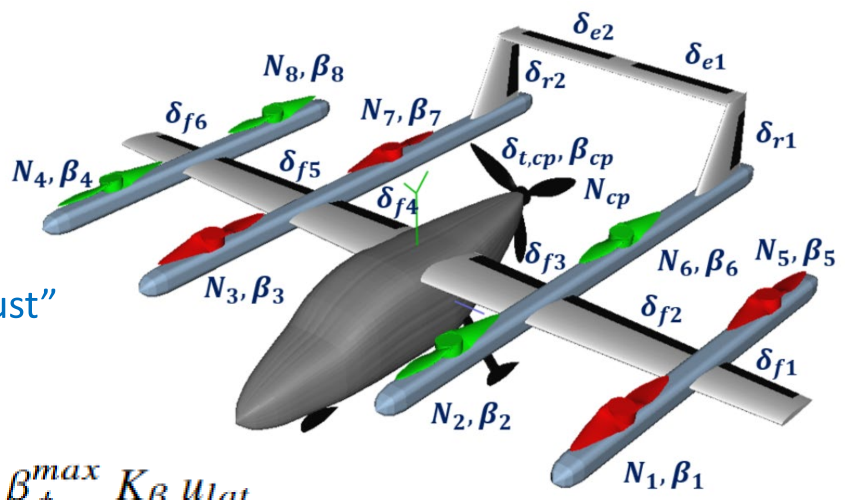
Common “thrust” component

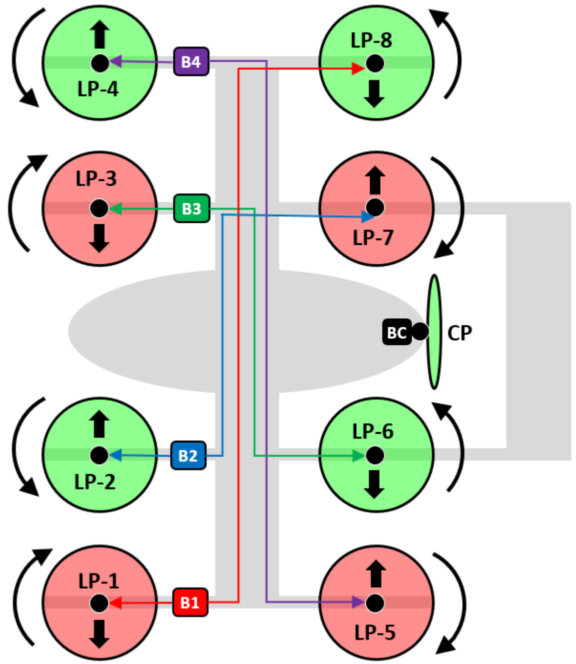
$$\beta_\phi = \beta_\phi^{max} K_\beta \, u_{lat}$$

$$\beta_\theta = \beta_\theta^{max} K_\beta \, u_{lon}$$

$$\beta_\psi = \beta_\psi^{max} K_\beta \, u_{dir}$$

KEAS	0	50	100	110	120	130	140	150	200+
K_β	1	1	1	0.75	0.50	0.25	0	0	0

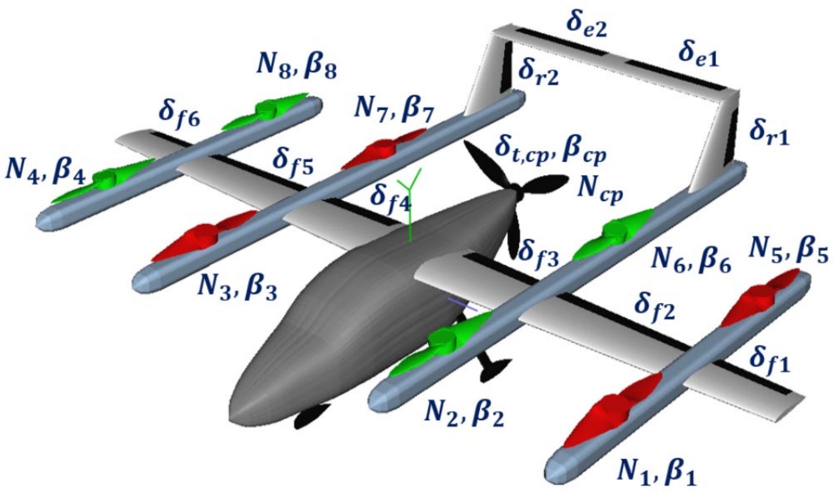




#	Symbol	Description	Unit
1-3	$\delta_{f1}, \delta_{f2}, \delta_{f3}$	Flaperon, left wing, out-/mid-/inboard	deg
4-6	$\delta_{f4}, \delta_{f5}, \delta_{f6}$	Flaperon, right wing, in-/mid-/outboard	deg
7, 8	δ_{e1}, δ_{e2}	Left, right elevator	deg
9, 10	δ_{r1}, δ_{r2}	Left, right rudder	deg
11	$\delta_{t,cp}$	Cruise propeller throttle setting	–
12	β_{cp}	Cruise propeller pitch	deg
13	N_{cp}	Cruise propeller RPM	RPM
14-21	$N_1 - N_8$	Lift propeller RPMs	RPM
22-29	$\beta_1 - \beta_8$	Lift propeller pitch	deg

Set-Point Logic for Lift Propulsors

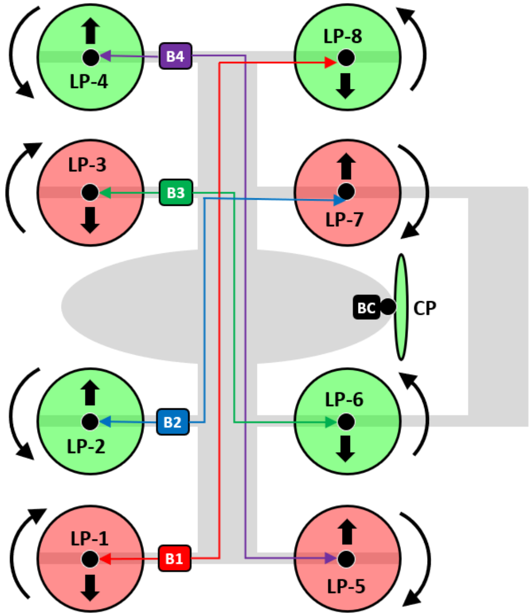
- Lift propeller RPMs: $N_1, \dots, N_8$
- Lift propeller blade pitch: $\beta_1, \dots, \beta_8$



- If fixed-pitch lift propellers are used:
  - Control thrust using RPM $N_1, \dots, N_8$
  - Concern: Can the RPM be varied fast enough for attitude control?

- If variable-pitch lift propellers are used:
  - Control thrust using blade pitch $\beta_1, \dots, \beta_8$
  - RPMs $N_1, \dots, N_8$ fixed at a given speed, and scheduled with speed

- **Considered for LPC-03:** variable-pitch lift propellers with set-point control
  - Vary thrust by varying blade pitch $\beta_1, \dots, \beta_8$ ("quicker" than RPM control)
  - Follow-up by slowly varying RPM to restore blade pitch to a nominal "set-point"
  - Short-term response: blade pitch change at constant RPM
  - Long-term response: RPM change with blade pitch remaining at set-point



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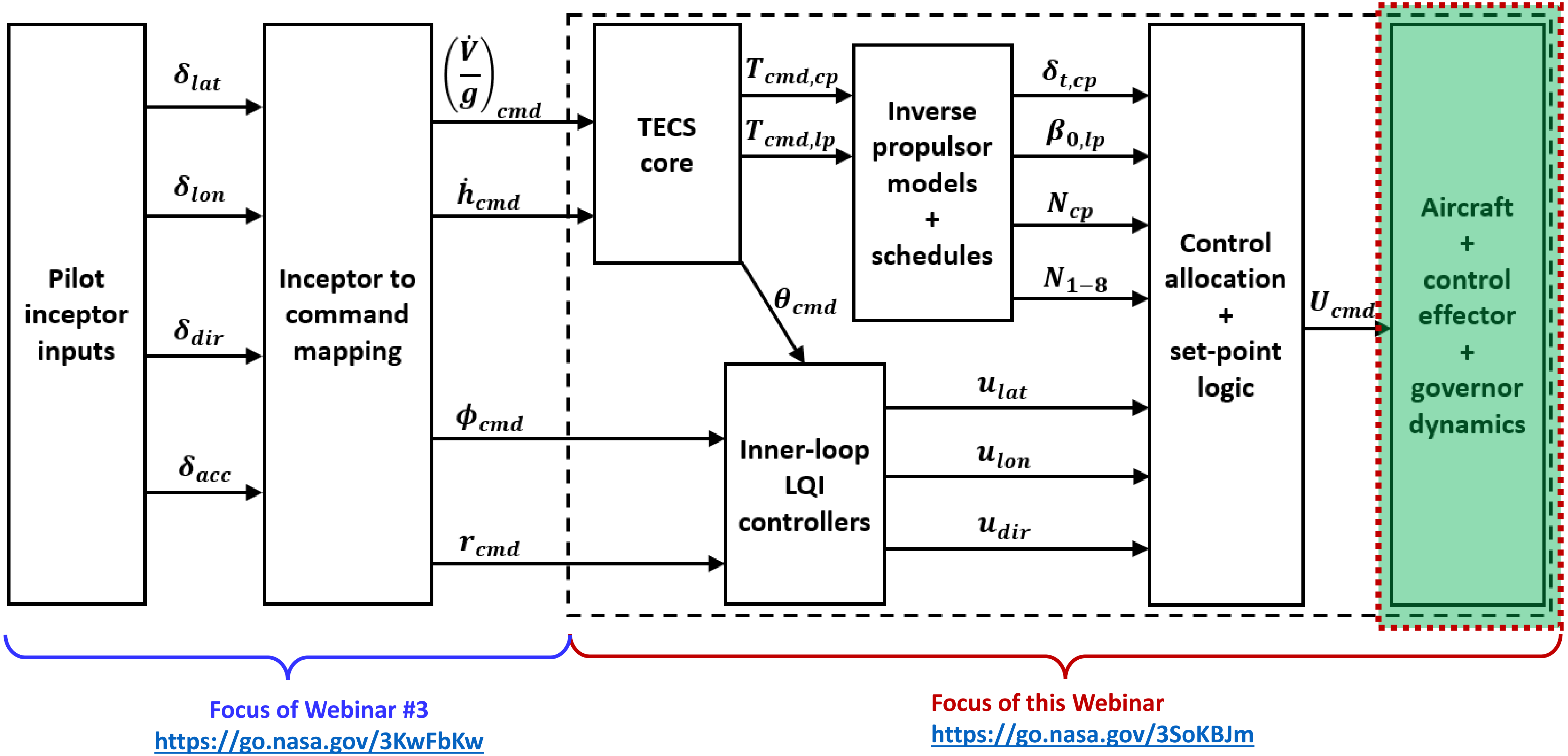
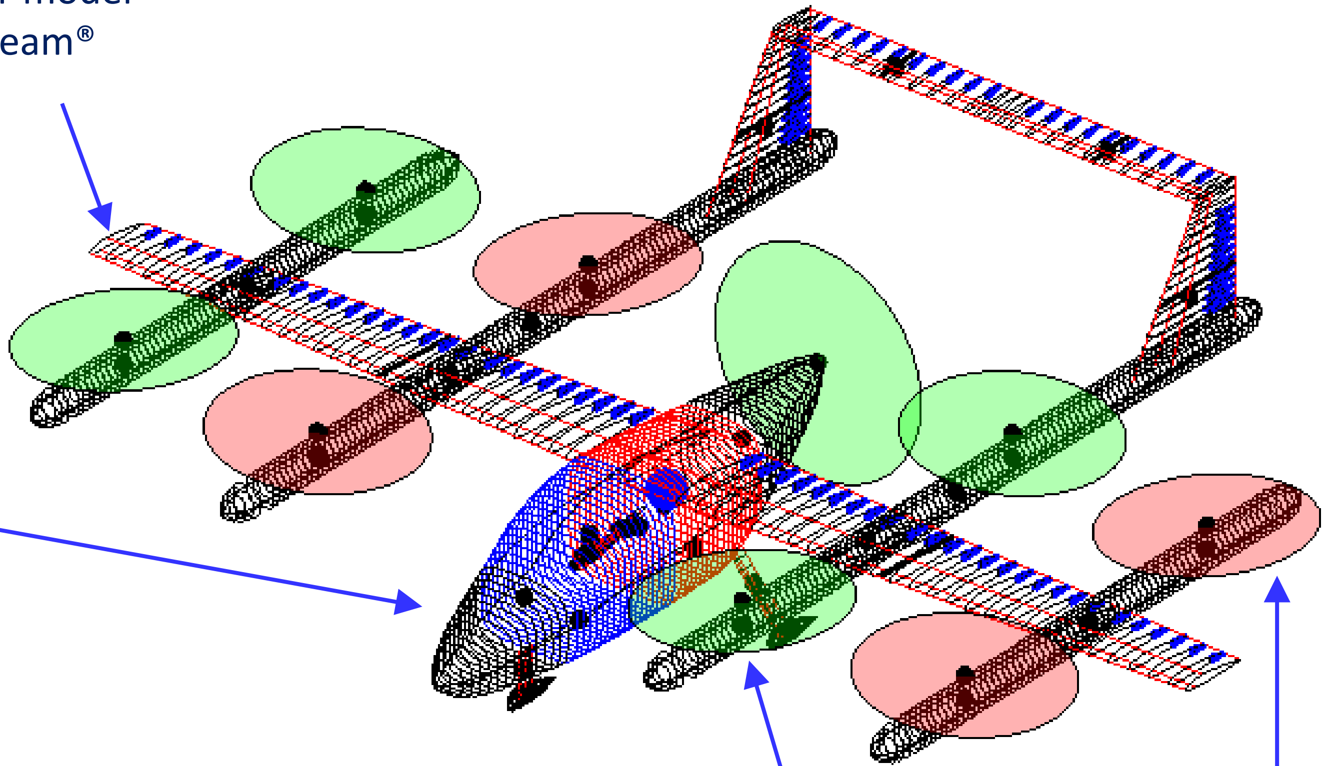
Flight Control System Architecture for LPC-03



Aircraft Dynamics: Aero-Propulsive Analysis Approach

Lifting surfaces: All lifting surfaces are discretized into strips. Strip sectional aero, downwash reduced order model generated using FlightStream®

Wireframe geometry model of aircraft within PEACE (MATLAB)



Geometry update rules:
These rules are specified during problem setup. They govern how the geometry of a component updates during sizing iterations, how components are located or mounted relative to other components, etc.

Non-strip geometry:
Loads are analyzed separately using FlightStream® to create lookup tables that are queried during sizing

Mass properties:
Mass: component weight equations for GA aircraft, plus calculated weights of propulsion & energy system components
CG & inertia: computed per component; summed appropriately

Propulsors: Modeled using a blade element momentum theory model coupled with a Pitt-Peters inflow model

Note:
For further details regarding modeling approach, see:
Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044

Control Effector and Governor Dynamics

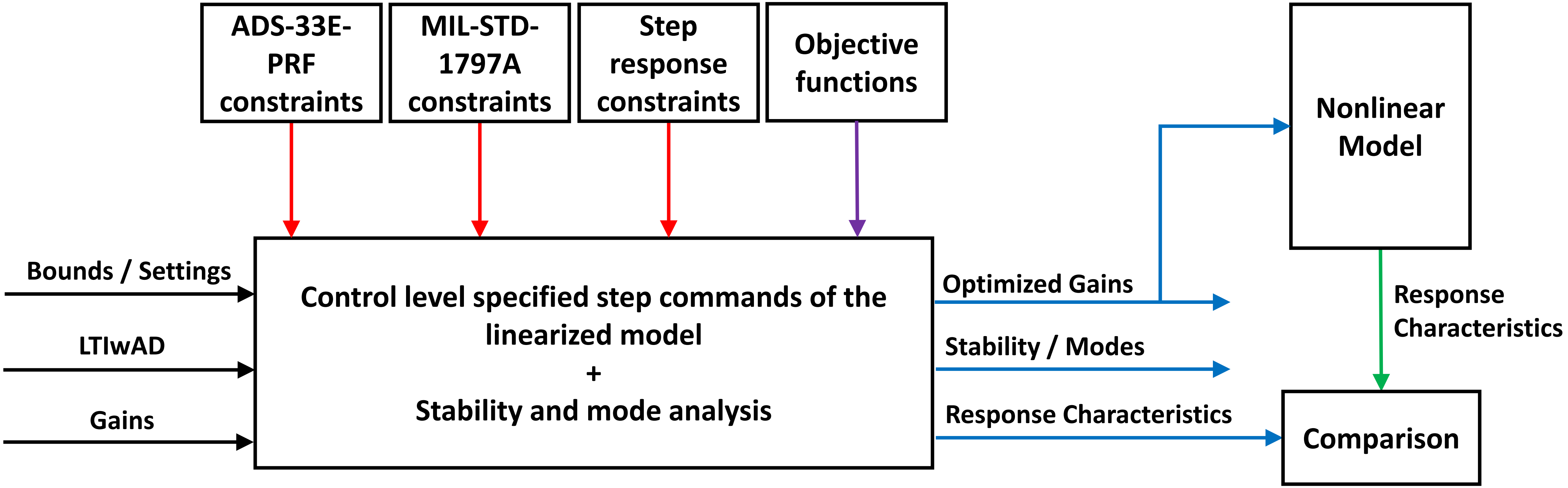
- Second order actuator dynamics are assumed for control surface and blade pitch actuators
  - Characterized by natural frequency ω_n and damping ratio ζ
- **Cruise propeller governor:**
  - Controls cruise prop blade pitch β_{cp} (subject to actuator dynamics) to maintain scheduled RPM
  - Regulates against variations in drive torque and aerodynamic load torque
- **Lift propeller governors:**
  - Control lift motor shaft-power to maintain set-point RPM
  - Regulate against aerodynamic load torque changes from freestream flow or blade pitch angle $\beta_1, \dots, \beta_8$

$$G_{act}(s) = \frac{\delta(s)}{\delta_{cmd}(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \implies \ddot{\delta}(t) + 2\zeta\omega_n\dot{\delta}(t) + \omega_n^2\delta(t) = \omega_n^2\delta_{cmd}(t)$$

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

Optimization of Flight Control System Parameters (Gains)

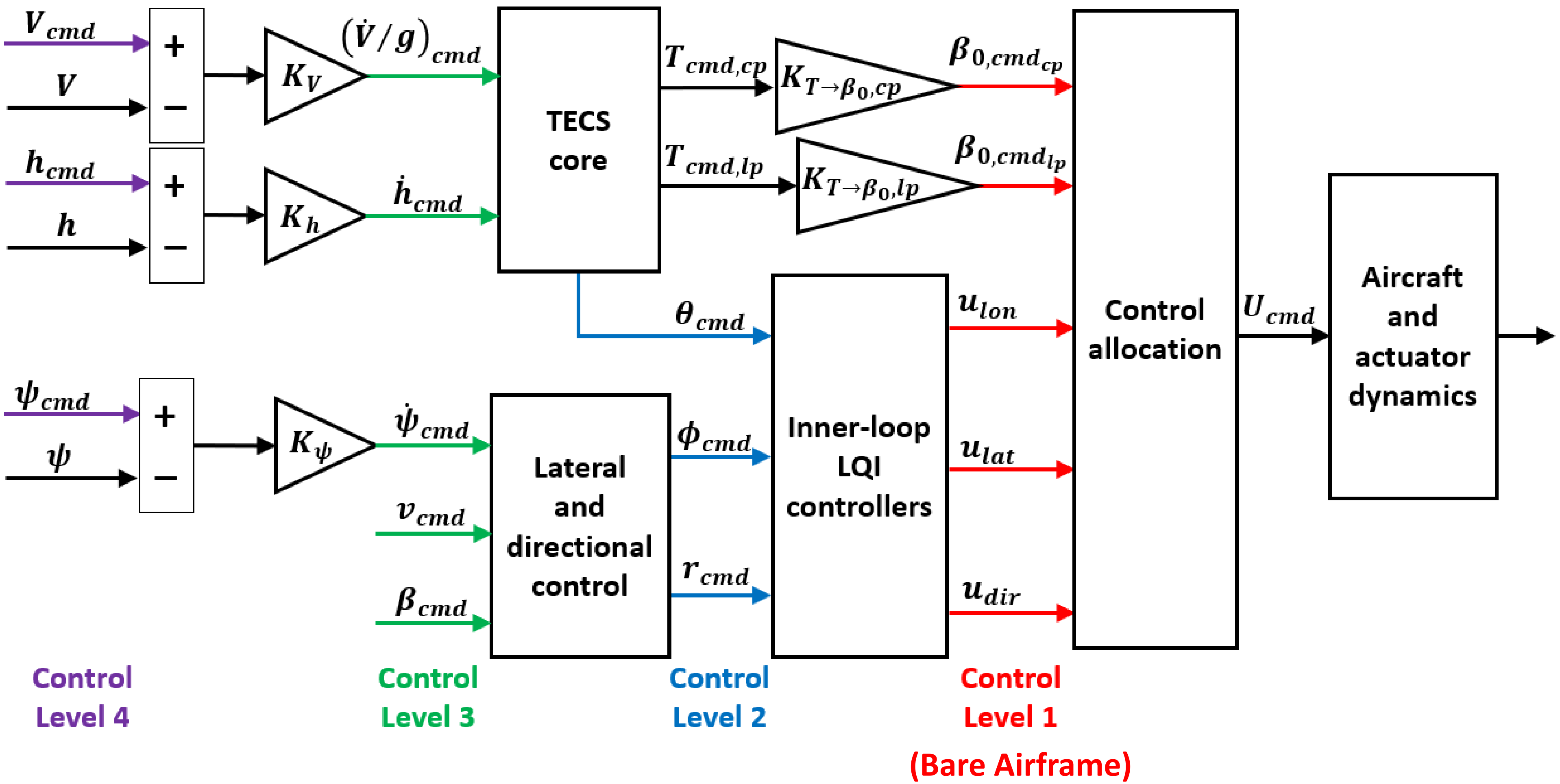
- **Nonlinear Simulation Model (NLS):** the "full nonlinear" model used for flight simulation (implemented in Simulink)
- **Linear Time-Invariant (System) with Actuator Dynamics (LTIwAD):** obtained from NLS by linearizing it at multiple trim points and augmenting with actuator dynamics
- The **LTIwAD** models at each trim condition are used by the MATLAB genetic algorithm optimizer (*ga*) to determine control system gains subject to several constraints
  - ADS-33E-PRF, MIL-STD-1797A, step response characteristics (e.g., rise time, settling time, overshoot)



For further details: Comer, A. and Chakraborty, I., **"Total Energy Flight Control Architecture Optimization for a Lift-Plus-Cruise Aircraft,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0399

Control Level Definitions

- Gains associated with Control Level 2 and Control Level 3 are first optimized
- Control Level 4 (outer loop) and feed-forward gains are optimized thereafter



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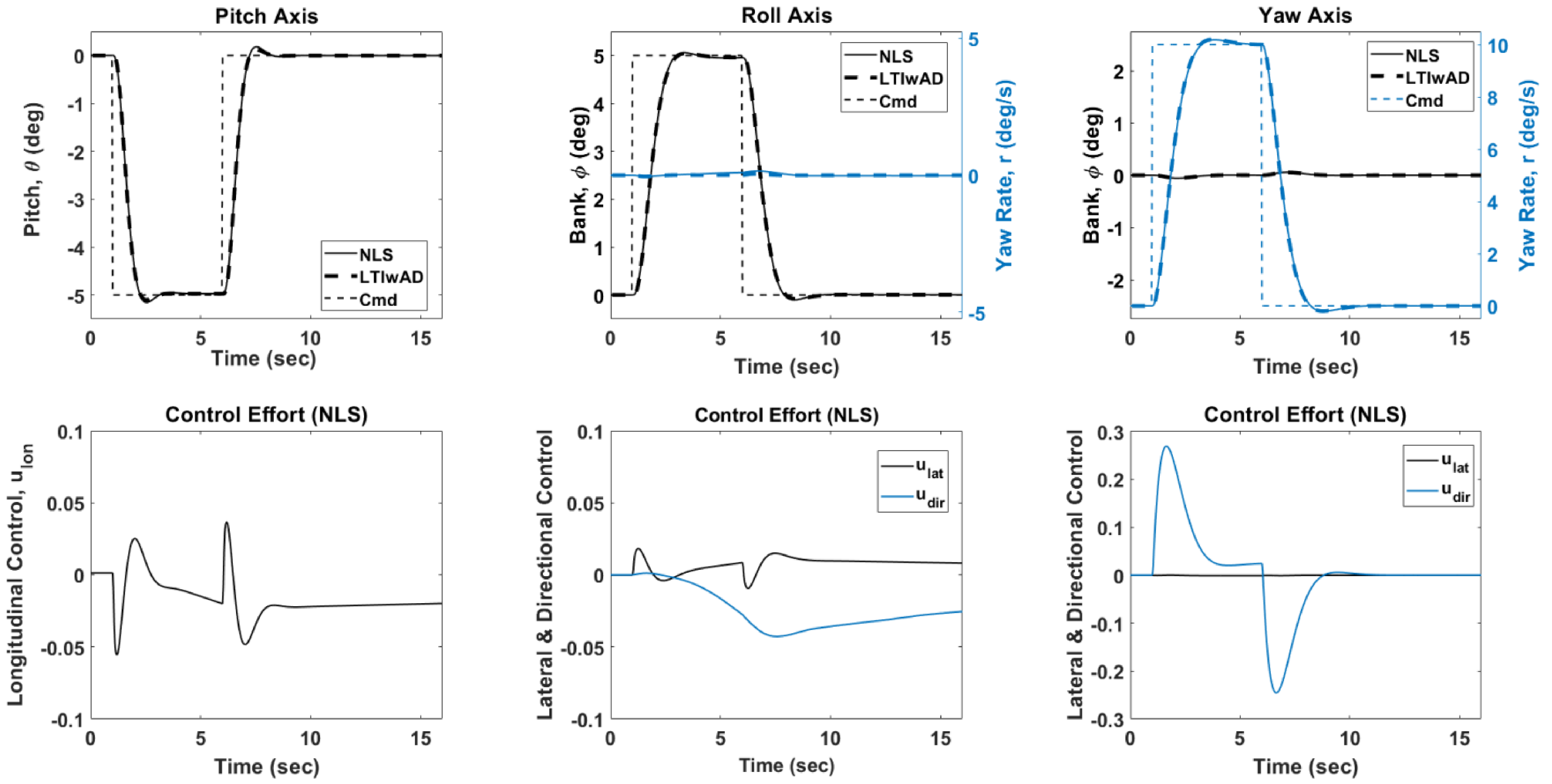
Inner-Loop Pulse Responses at Hover



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Bank Angle and Lateral Velocity Pulse Responses (starting from Hover)

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Interesting fact:
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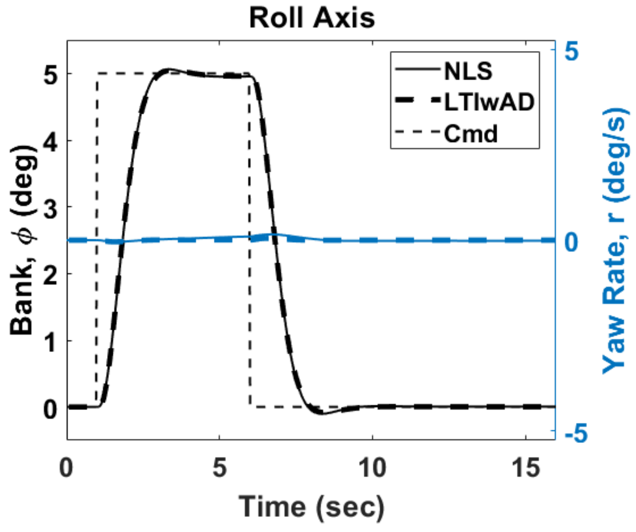
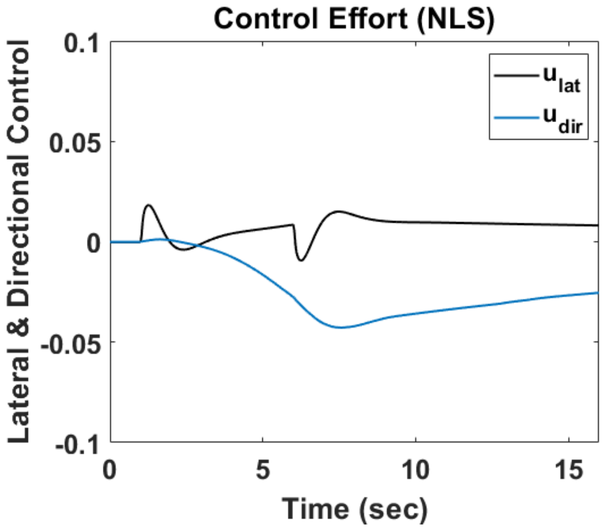
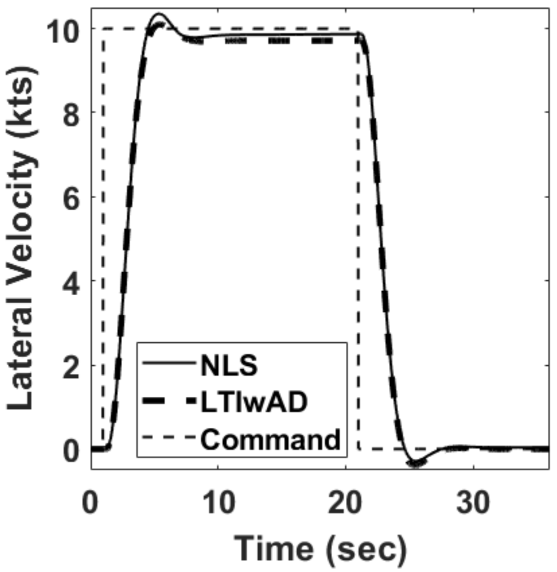
Piloted simulations considered both these scenarios, one in each sim

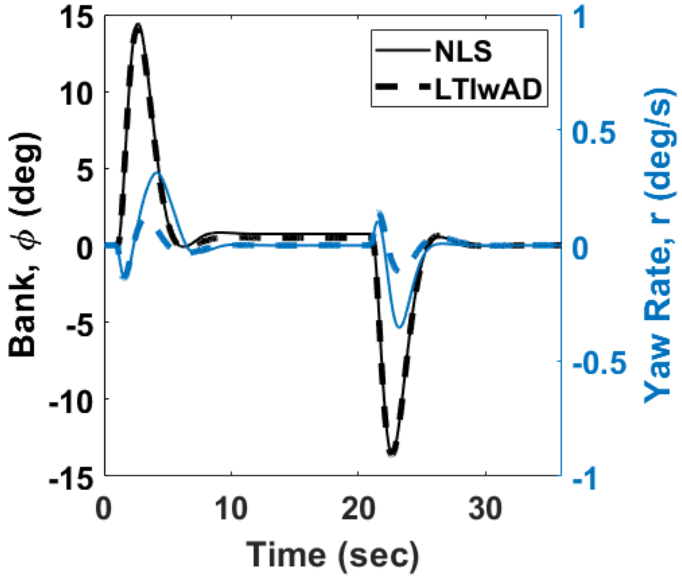
Bank angle pulse command
(e.g., Pilot inceptor commands bank angle)

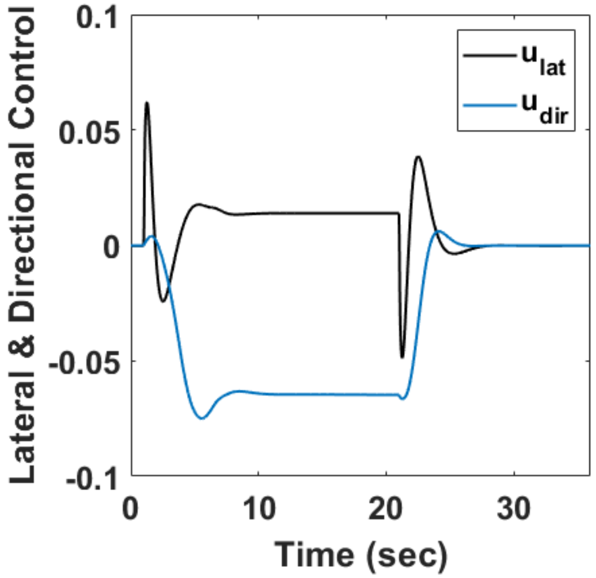




Lateral velocity pulse command
(e.g., Pilot inceptor commands lateral velocity)



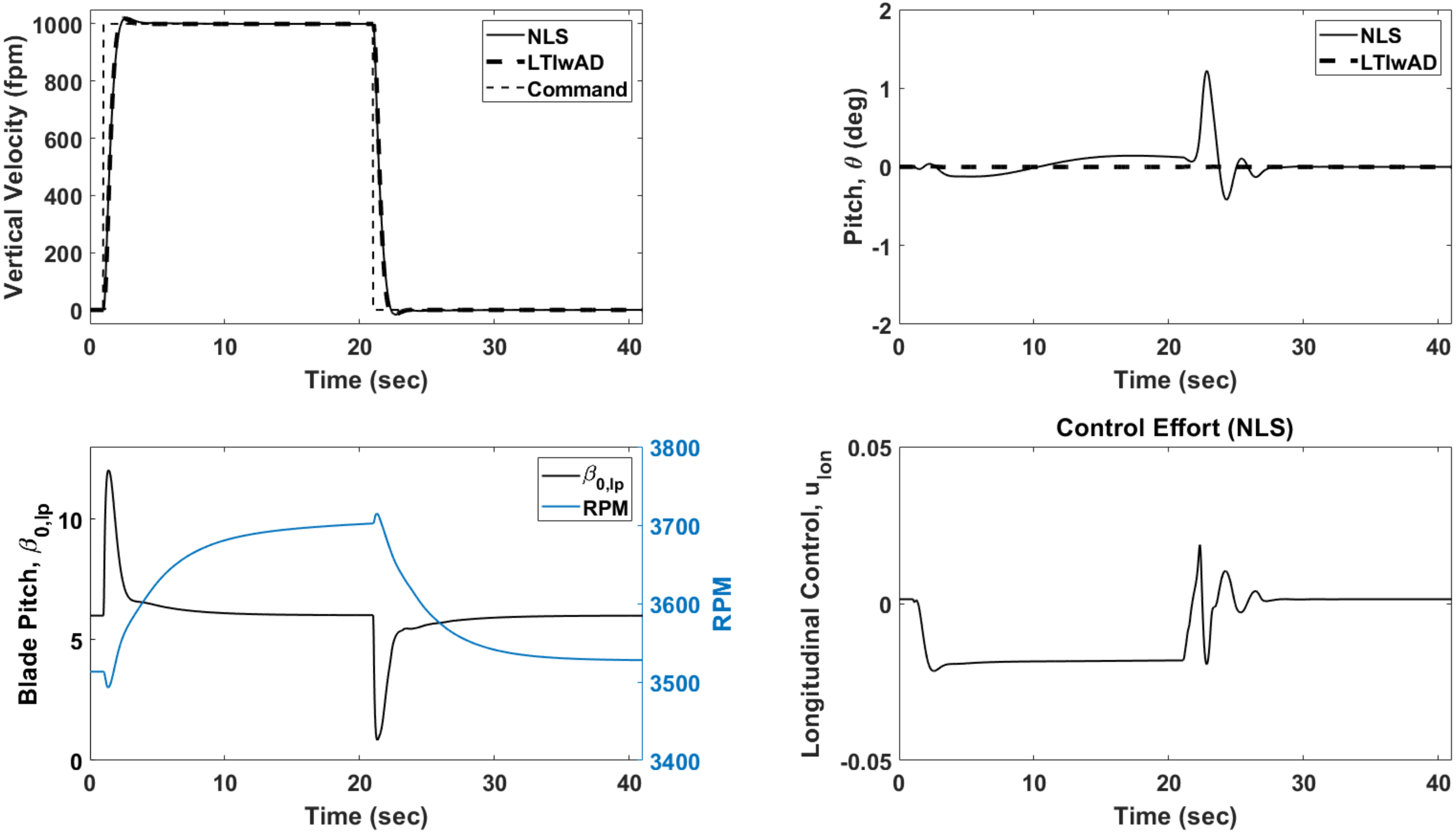




Vertical Velocity Pulse - Hover

Scenario:
Pilot inceptor generates a vertical velocity command in VFM

This was tested through piloted simulations in two simulators (Webinar #3)



Vertical Velocity Ramp Response in Forward Flight (FPARC/FPAH)

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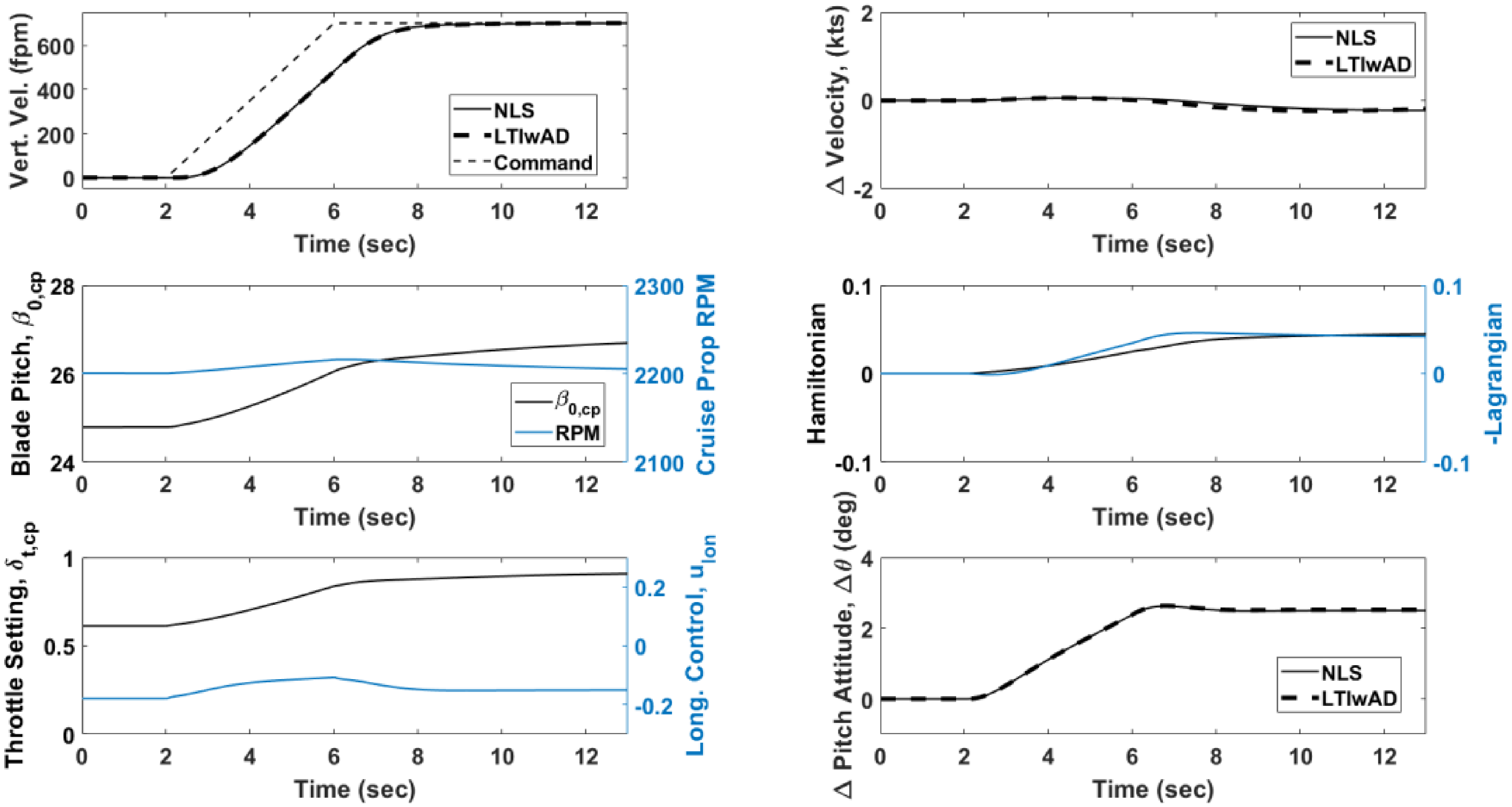
One simulator used in piloted simulation tests used FPARC/FPAH in forward flight mode.

Pilot inceptor generates FPA rate command (FPARC).

Centering inceptor sets FPA hold (FPAH)

(Webinar #3)



TECS Path Priority and Speed Priority in Forward Flight (part of Envelope Protection)

Nominal
(cruise prop "throttle" not saturated)

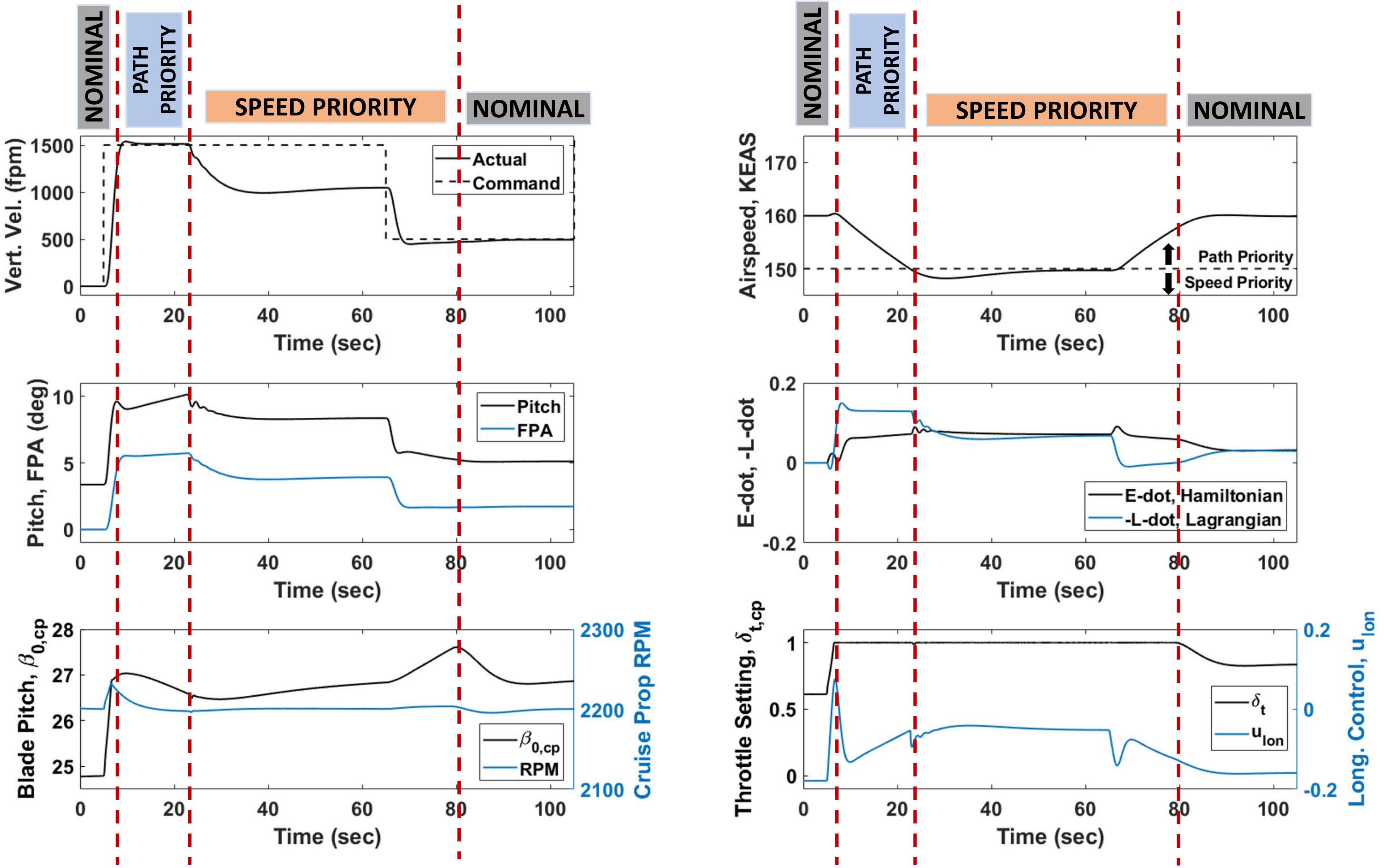
Both path and speed commands are tracked

Path Priority
("throttle" saturated)

Path command tracked. Speed goes "open-loop"

Speed Priority
("throttle" saturated)

Speed command tracked. Flightpath goes "open-loop"



Transition from Vertical Flight Mode to Forward Flight Mode (Departure Transition)

- Link to video: https://youtu.be/D-M-Zs26Xfs?t=581

Transition from Forward Flight Mode to Vertical Flight Mode (Arrival Transition)

- Link to video: https://youtu.be/D-M-Zs26Xfs?t=788

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Conclusions

- A flight control system based on the Total Energy Control System (TECS) algorithm was implemented and optimized for a Lift-plus-Cruise (LPC) Urban Air Mobility (UAM) aircraft
  - The goal is to enable Simplified Vehicle Operations (SVO)
- The aircraft and control system models were implemented in Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP) – a MATLAB/Simulink-based S&C and flight simulation framework
- **Coming up:**
  - This FCS architecture will be paired with two different inceptor schemes (different designs & inceptor-to-command mappings)
  - Piloted simulations conducted in two flight simulators with (i) certified flight instructors, (ii) pilot license holders, and (iii) non-pilots (holding driver licenses)
  - Webinar #3, March 8, 1 pm Eastern, https://go.nasa.gov/41jqoJ5 (NASA) https://go.nasa.gov/3EzV3bc (public)