National Aeronautics and
Space Administration

Flight Dynamics Modeling for a Rapid Conceptual Development Environment

07/31/2024

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SYSTEMS ANALYSIS AND CONCEPTS DIRECTORATE

Project Overview

- Motivation
- Objectives
- Method Development
- Example Simulations
- Future Work

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Rapid Conceptual Development Environment (RapCDE)

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Rapid Conceptual Development Environment

- Goal - A highly integrated aircraft development environment capable of:
  - Rapidly maturing ideas into conceptual designs
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Tool modularity

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- Initial application to Regional Air Mobility (RAM) aircraft

Project Objectives

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- Current RapCDE components:

Geometry

Aerodynamics

Weights

Mission

Battery Performance

Python/Wrapper

MATLAB/Simulink

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- Current RapCDE components:

Geometry
Aerodynamics
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Mission
Battery Performance

- This work presents the development and integration of:

Flight Dynamics
Flight Simulation

Python/Wrapper
MATLAB/Simulink

Project Objectives

Flight Dynamics Modeling (FDM)

Methods to create Simulink models for:

- Aerodynamic forces and moments
- Propulsion system forces and moments

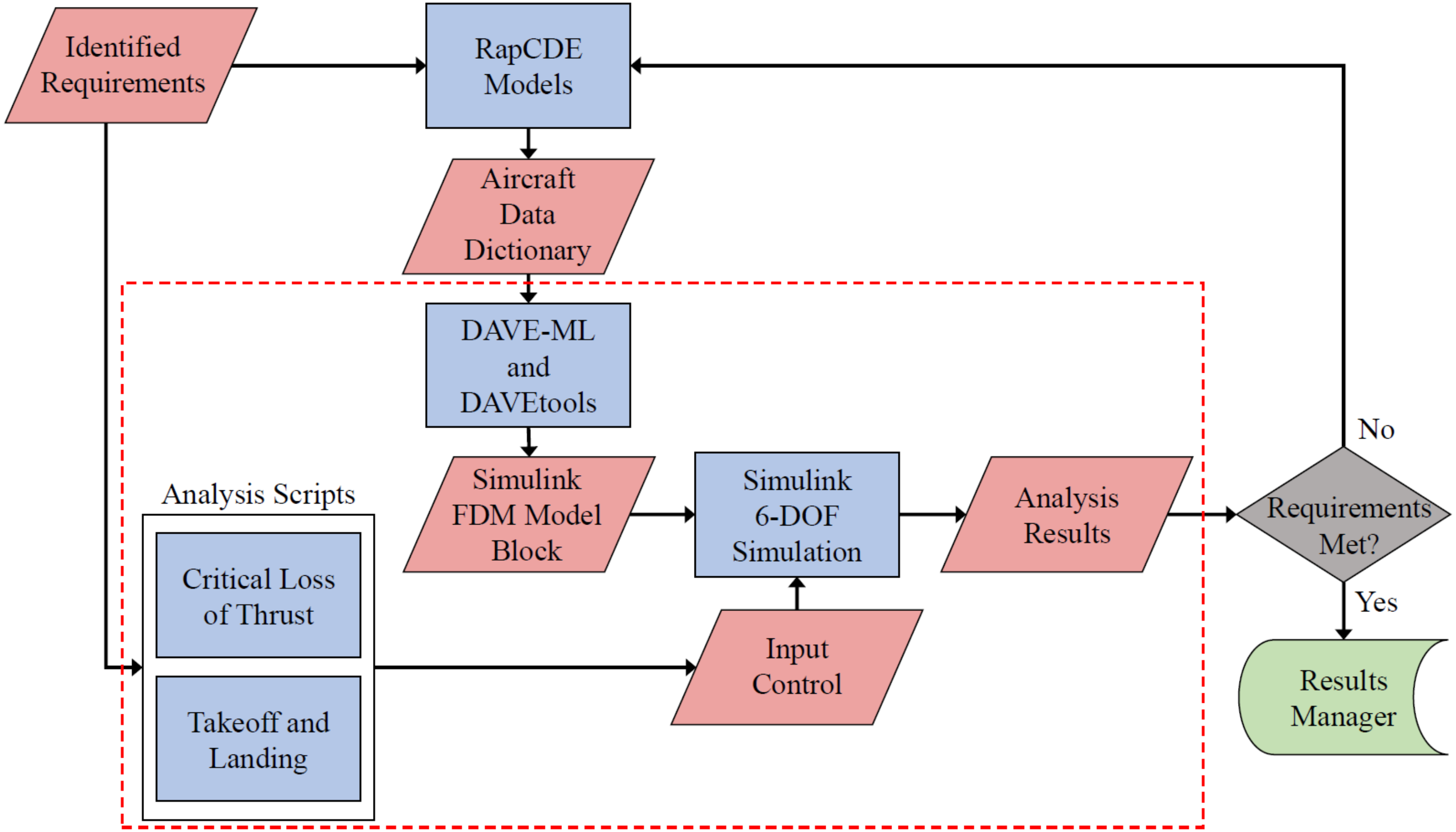
Flight Simulation

Develop simulation tools to evaluate:

- Trim capabilities
- Takeoff performance
- Landing performance
- Critical loss of thrust (CLOT)

Flight Dynamics Modeling and Simulink-Based Flight Simulation

RapCDE Simulation Framework



- Process

- Input/Interim

- Output

Flight Dynamics Models – DAVE-ML

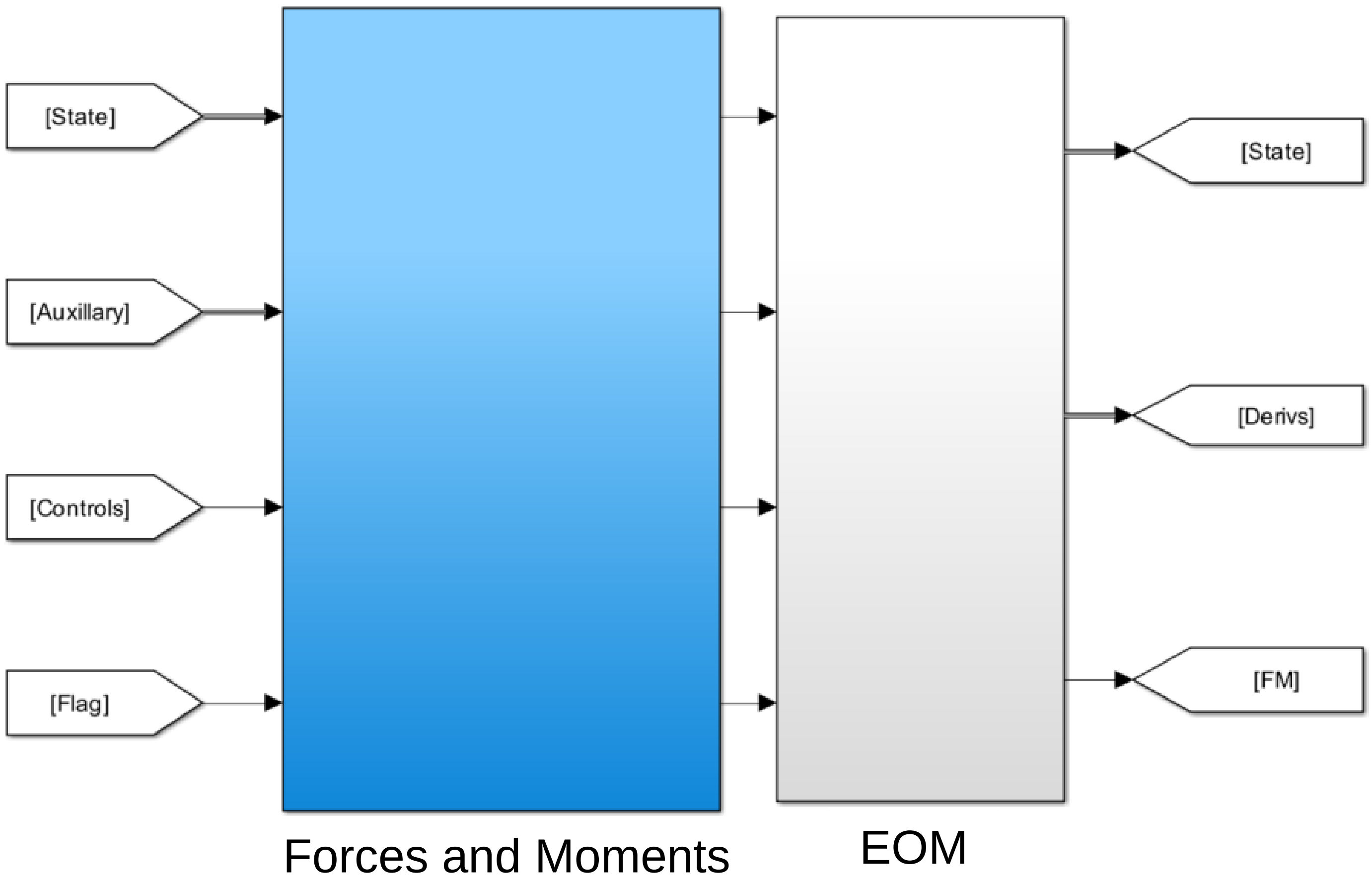
<u>DAVE-ML – A Flight Dynamics Model Exchange:</u>

- Application of the Extensible Markup Language (XML)
- **Standardized formatting** of flight dynamics models
  - Inputs, outputs, internal functions
- Gridded/ungridded interpolation
- DAVEtools – Automatic Simulink model block generation

https://daveml.org/

Simulink-Based Flight Simulation

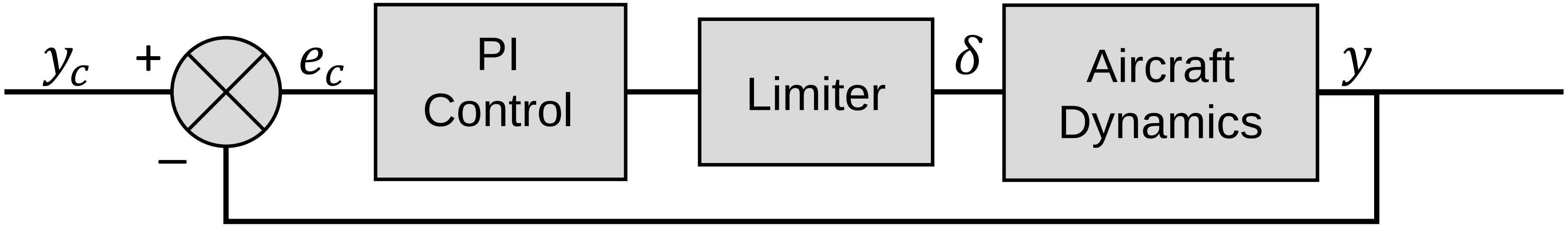
- NASA Generic Transport Model:
  - Trim algorithm
  - Equations of motion
- Developed models:
  - Aerodynamics
  - Multi-engine propulsion
  - Ground forces
  - Takeoff and landing controllers



Control Design

Control Design

- Goal – Emulate piloted takeoff and landing:
  - PI controllers – initial proof of concept – gains tuned manually
  - Takeoff – climb angle
  - Landing – glide path to flare path transition and airspeed



Variable (y)	Input (δ)
Bank angle, ϕ	Aileron, δ_a
Yaw Rate, r	Rudder, δ_r
Climb angle, γ	Elevator, δ_e
EAS	Throttle, τ

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Aerodynamic Modeling

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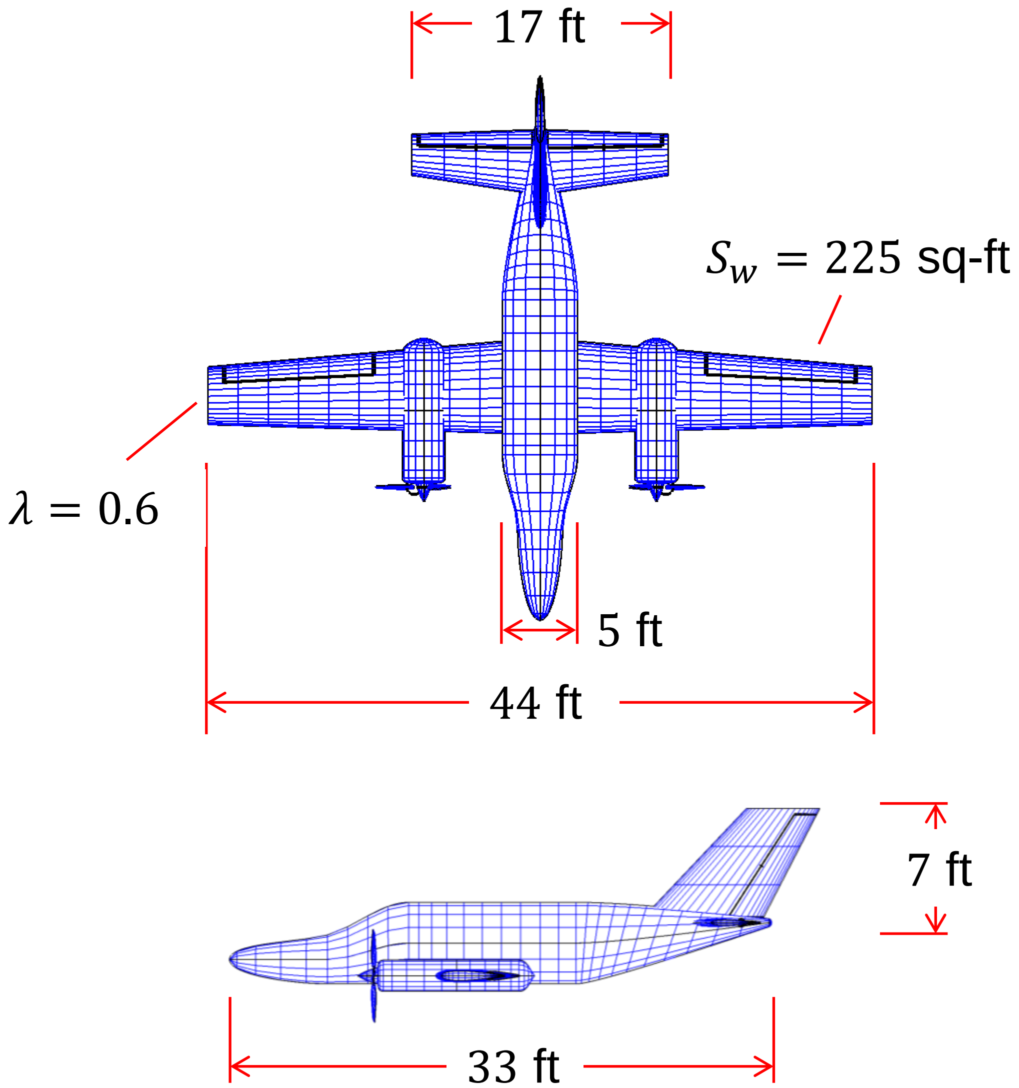
Aerodynamic Modeling

- Example aircraft – Similar to existing twin-engine light transport aircraft:
  - Level 3, low speed
- Defined in RapCDE:
  - Main wing/stabilizers
  - Fuselage
- Propulsion System:
  - FLOPS engine deck data



Aerodynamic Modeling

- VSPAero aerodynamic data:
  - Combination of discrete sample points
  - Damping derivatives from stability analysis mode
- Computational time:
  - Longer than desired
  - Alternative/smarter sampling approaches are needed

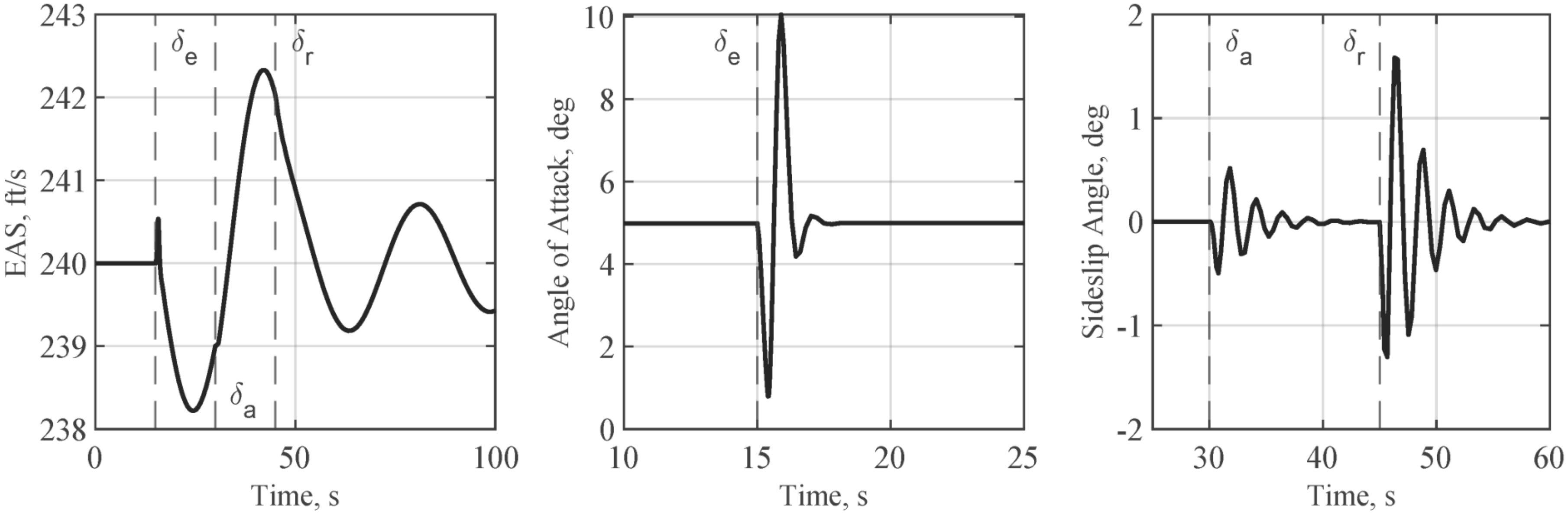
Analysis Parameters	Sampled Values
Angle of attack (α), deg	[-5.0, 0.0, 5.0, 10.0, 15.0, 20.0, 25.0]
Sideslip angle (β), deg	[-10.0, 0.0, 10.0]
Control Surfaces $(\delta_a, \delta_e, \delta_r)$, deg	[-15.0, 0.0, 15.0]
Mach Number	[0.1, 0.3]

N = 1,134 points ≈ 45 minutes

Example Results – Simulations

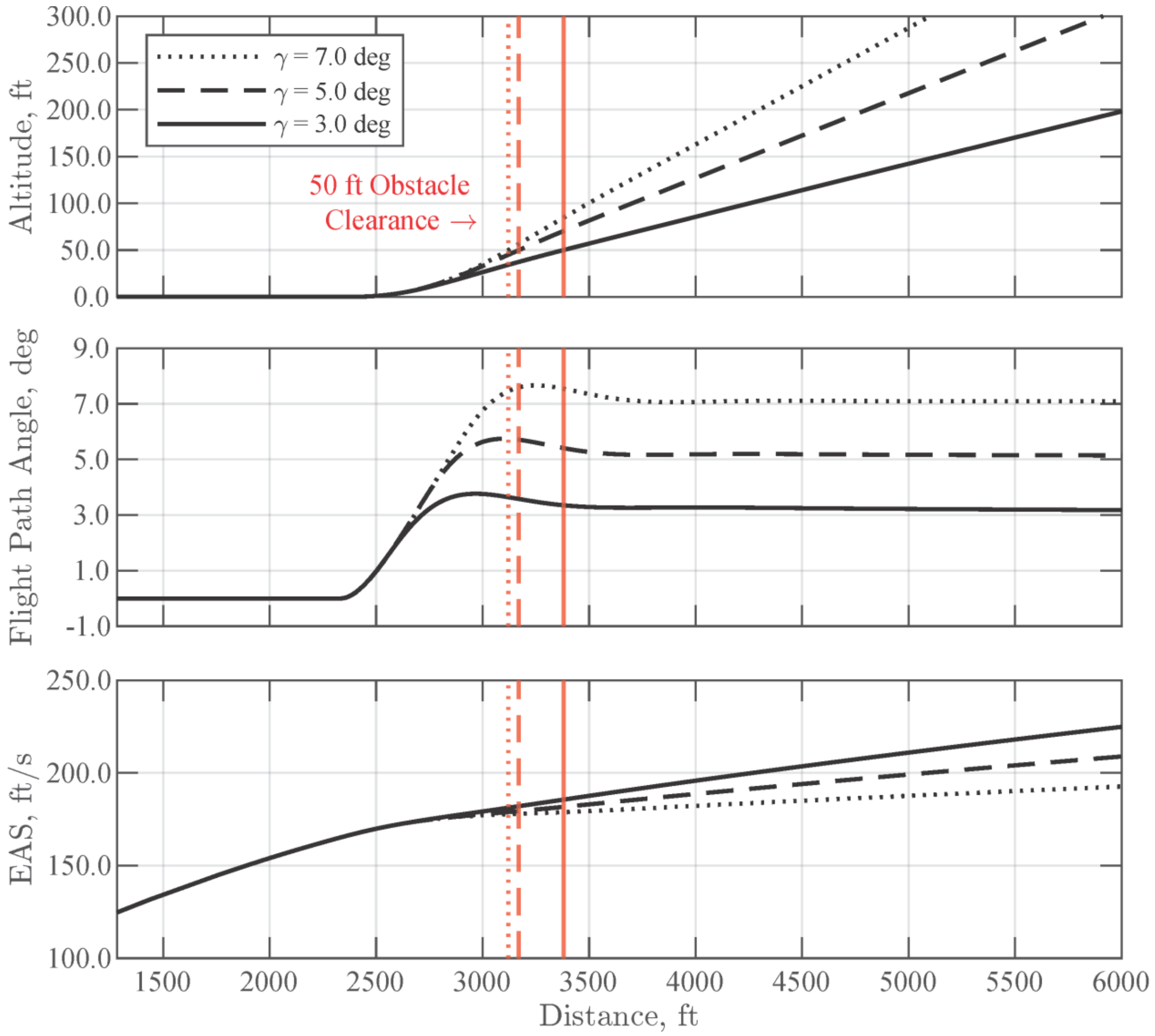
Doublet Response Simulation

- Trimmed at 240 ft/s cruise condition
- Control deflection inputs every 15 seconds
- Exhibits phugoid, short period, and Dutch roll modes



Takeoff Performance Simulation

- Maximum throttle setting
- Specify target climb angle:
  - 14 CFR Part 23 - 2.3 deg minimum
- Rotation initiated at:
  - $V_R \approx 145$ ft/s
  - ~ 1800 ft
- 250 ft difference in takeoff distance
- Future work will identify maximum achievable climb angles



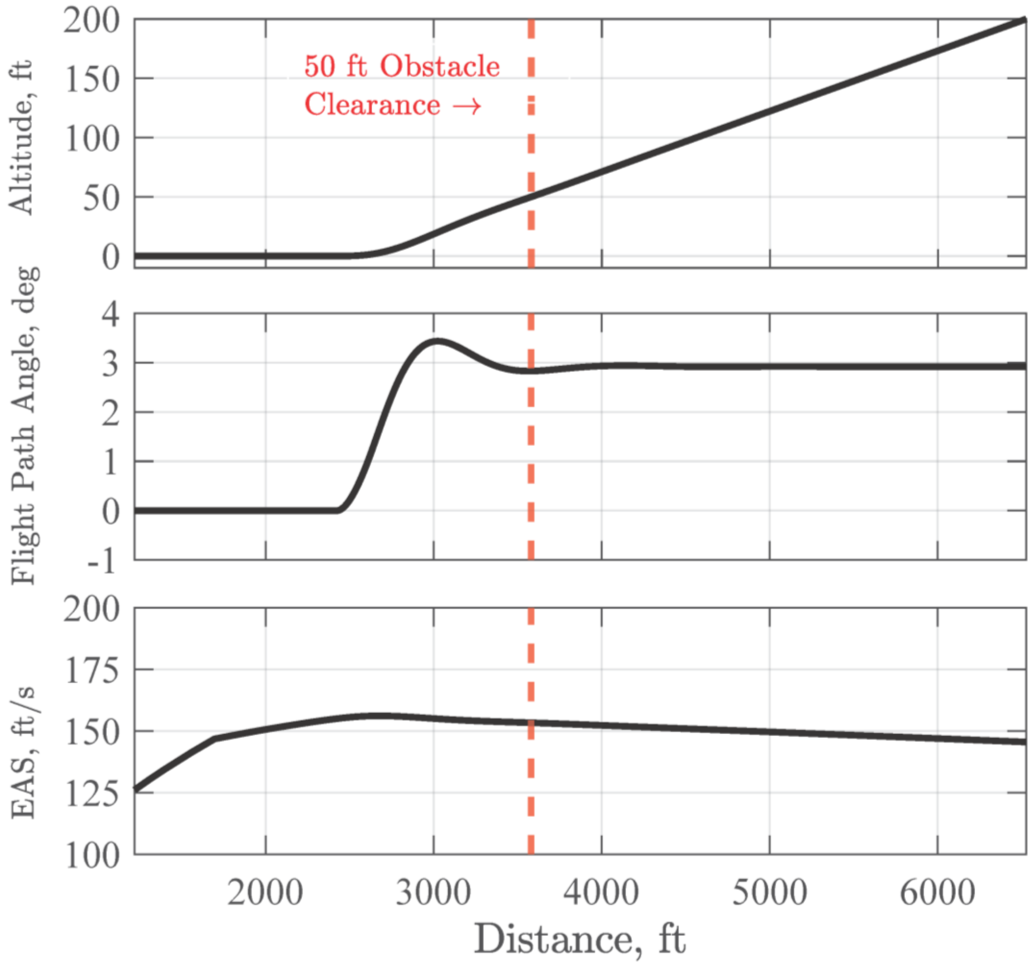
CLOT Trim Analysis

- Trim solutions at different target states
- Critical loss of thrust solutions:
    - Asymmetric thrust
    - Increase in control surface deflections and throttle setting

Level Flight, 230 ft/s			Climb, γ = 2.0 deg, 158 ft/s	
Nominal	**CLOT**	**Parameter [Limits]**	**Nominal**	**CLOT**
5.44	5.43	α, deg [-]	11.42	11.40
-0.04	0.12	δ_a, deg [-25,25]	-0.09	0.33
-4.80	-4.74	δ_e, deg [-25,25]	-8.85	-8.69
-0.01	-3.84	δ_r, deg [-25,25]	0.02	$\boxed{-12.43}$
0.48	0.98	Throttle [0,1]	0.47	$\boxed{0.96}$

CLOT Takeoff Simulation

- Similar procedure to full thrust takeoff simulation
- Target climb angle of 3.0 deg
- Left engine disabled at V_R
- Obstacle clearance 300 ft greater than full thrust simulation
- Airspeed is decreasing due to thrust lapse with altitude



Concluding Remarks

Developed FDM and simulation methods for use in RapCDE:

- VSPAero → DAVE-ML → Simulink
- Simulink-based flight simulation model
- PI controller design
- Example cases:
  - Doublet response
  - Takeoff analysis
  - Trim solutions
  - CLOT takeoff analysis
  - Landing analysis – **presented in paper**

Future Work

- Improve RapCDE aerodynamic data sampling techniques:
  - Reduce computation time
- Automate control gain tuning:
  - Simulink control toolbox
  - Update control methods
- Refine and implement methods for complete RapCDE studies:
  - Identify maximum climb rates instead of requiring them as input
  - Establish performance checks versus 14 CFR Part 23 standards

Acknowledgements

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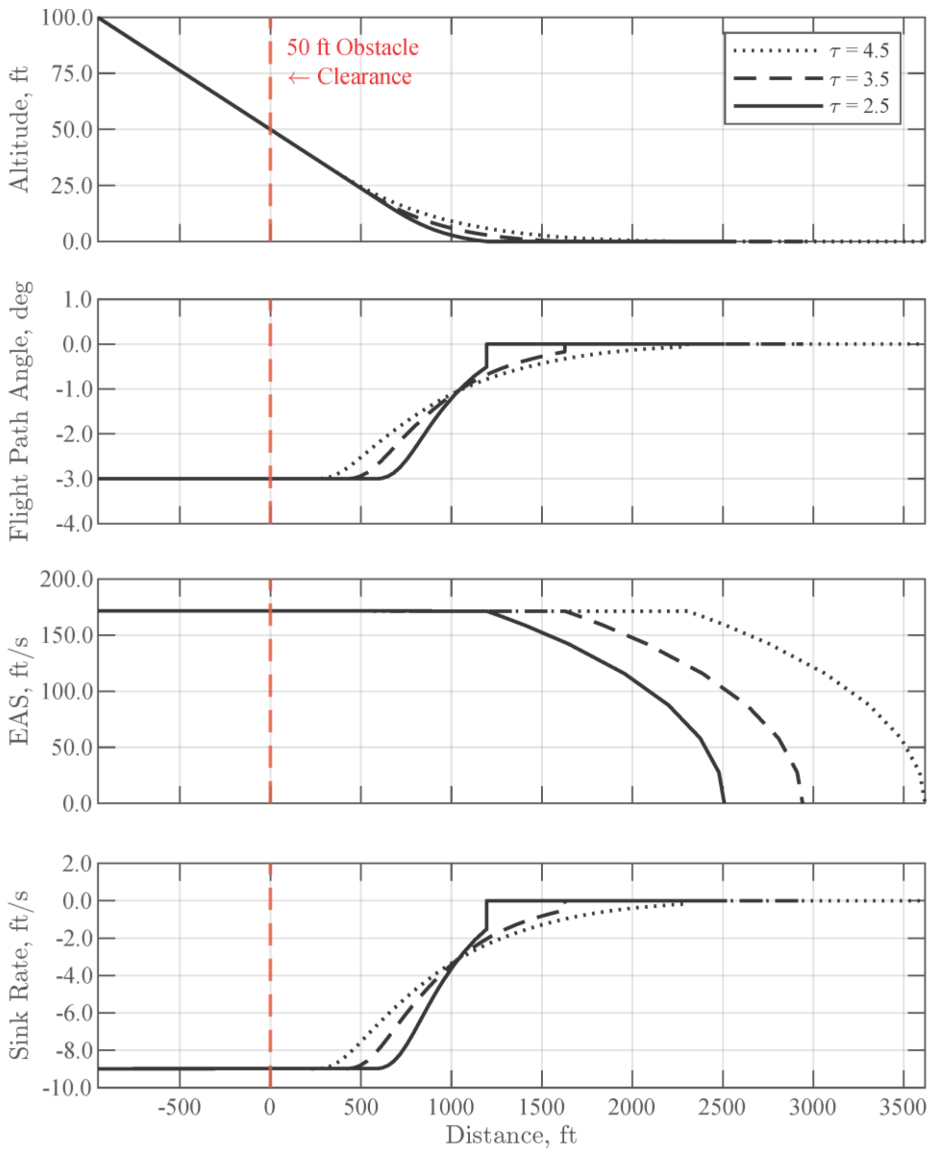
Thank You!

Questions?

Backup Slides

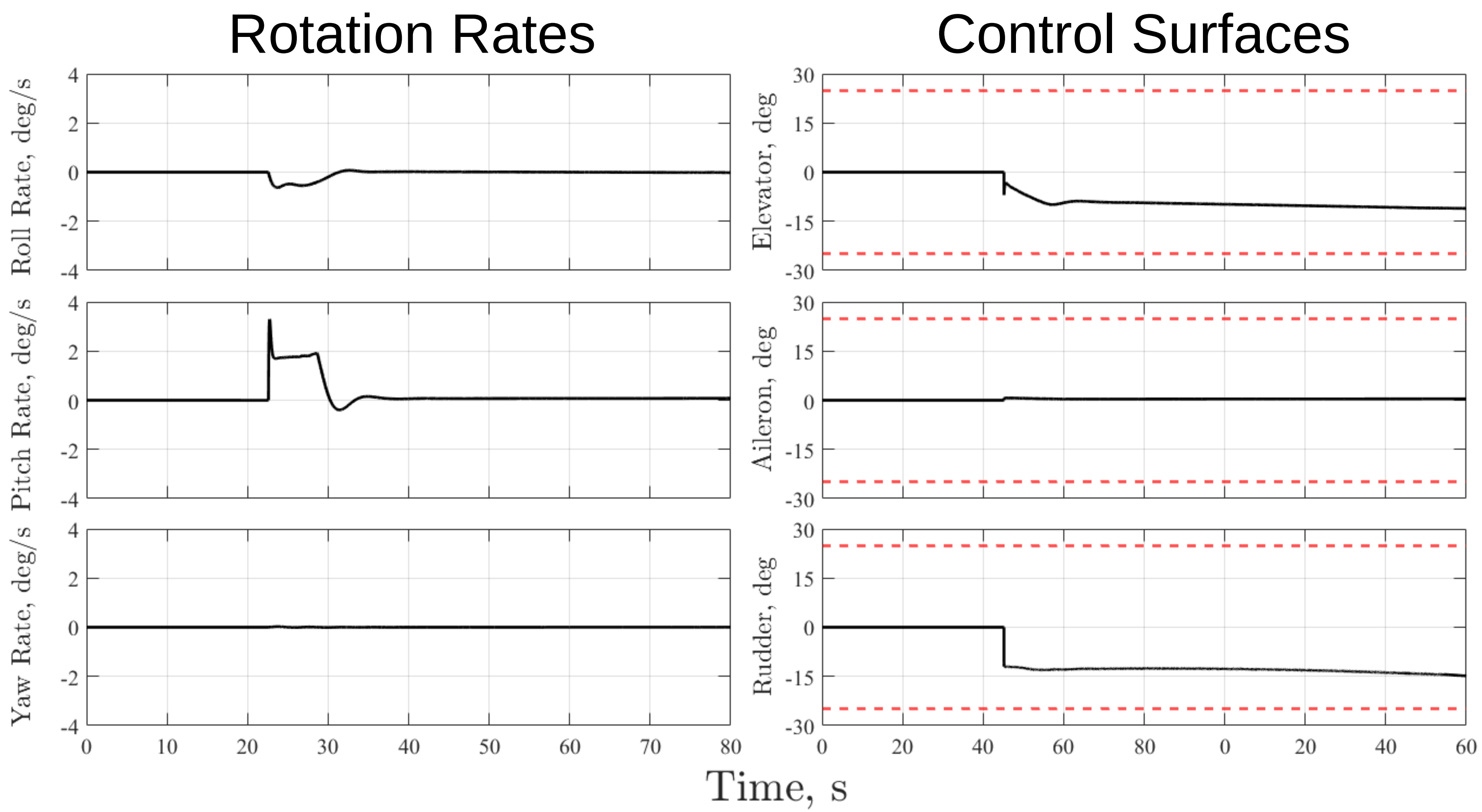
Landing Performance Simulation

- Target glide slope = -3 deg
- Reference airspeed on approach:
  - $V_{REF} \approx 172$ ft/s
- Flare path time constants of $\tau = 2.5, 3.5, 4.5$
- 1100 ft difference in landing distance
- Sink rates at touchdown between $0.2 - 1.5$ ft/s

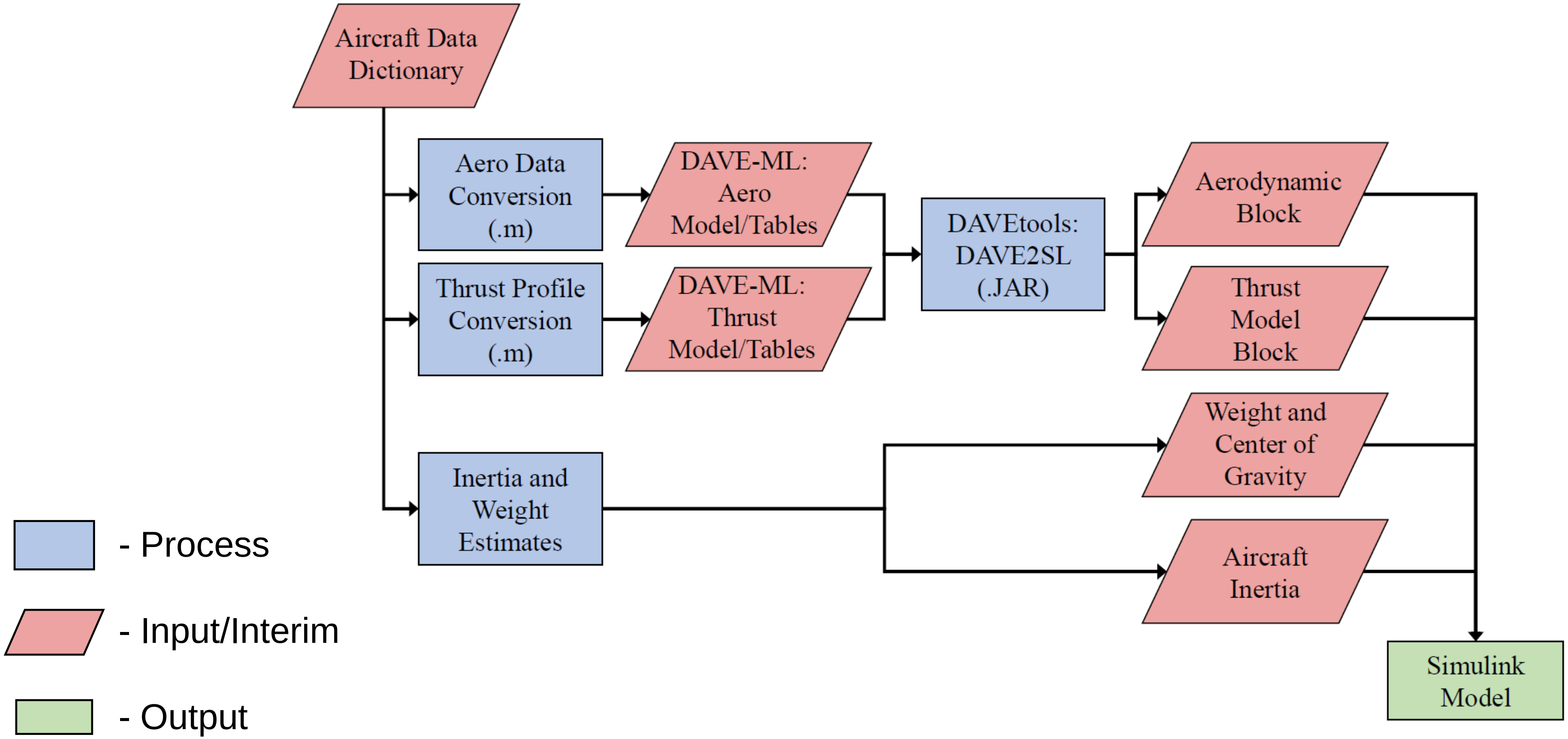


CLOT Takeoff Simulation

- Rotation rates and control surface deflections within reasonable limits

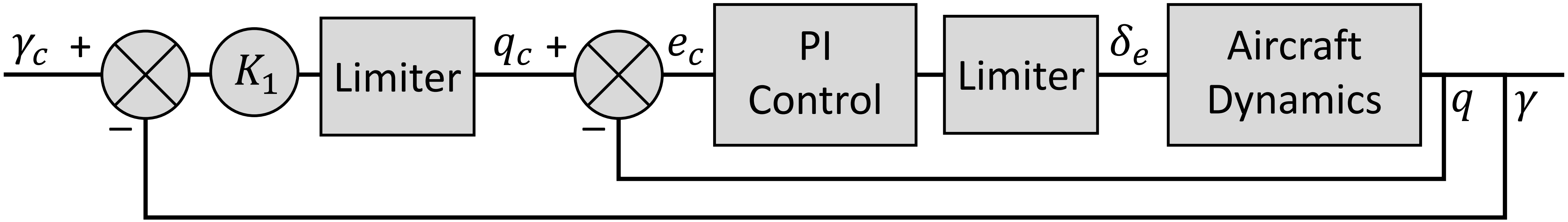


DAVE-ML Workflow

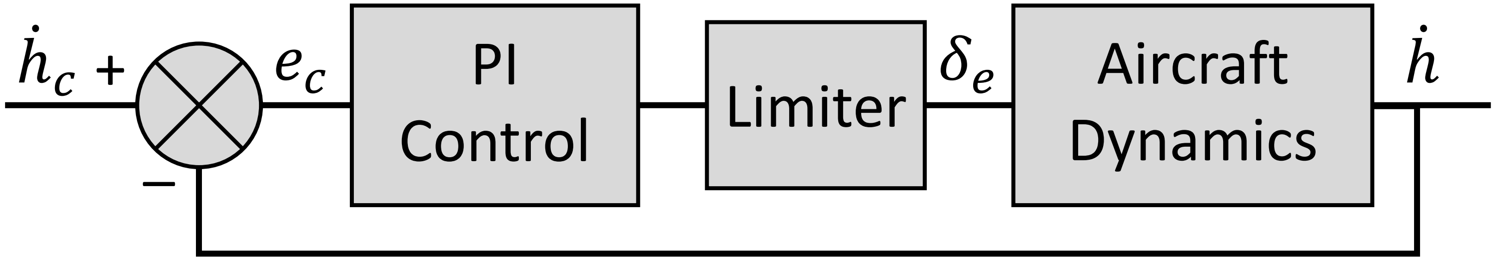


Control Design

- **Flight path angle** (glide slope) control



- **Flare path** (sink rate) control



Control Design – Flare Path

- Exponential flare path
- Target descent rate defined by:
  - R – glide slope to touchdown distance
  - n – number of time constants (τ) on flare path
- Measured descent rate assuming small glide path angles
  - $\dot{h} = -V\gamma$

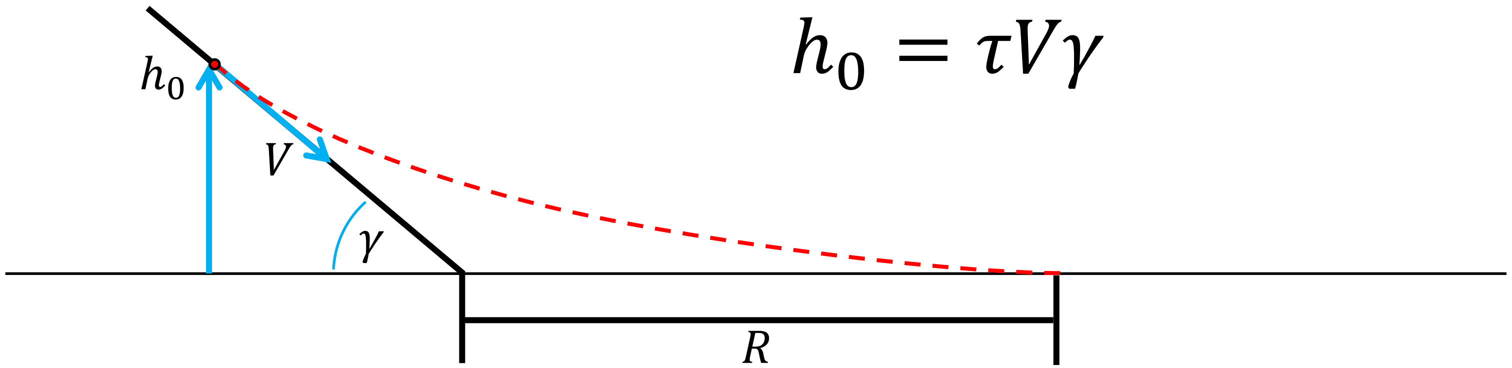
$$h(t) = h_0 e^{\frac{-t}{\tau}}$$

$$\dot{h}_c = -\frac{V(n-1)}{R} h$$

$$\tau = \frac{R}{V(n-1)}$$

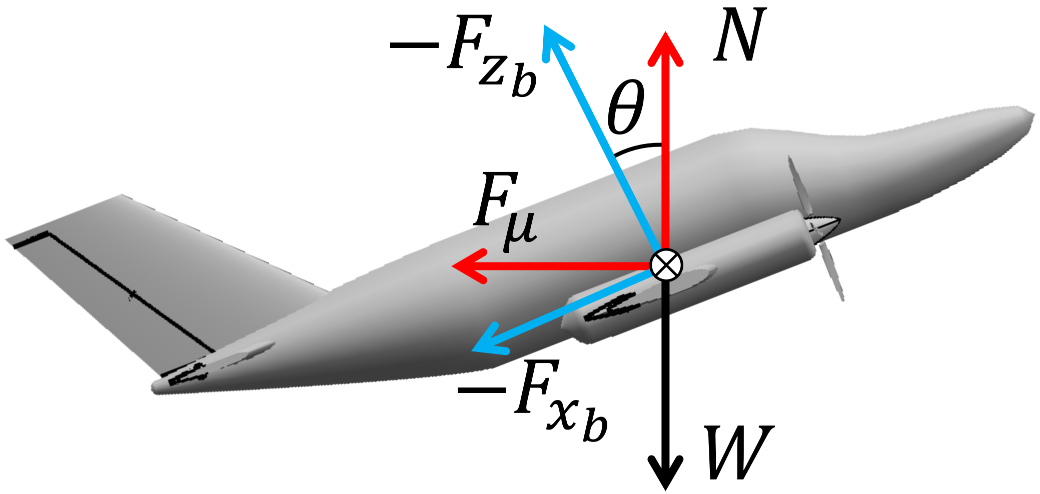
*Not throttle

$$h_0 = \tau V \gamma$$



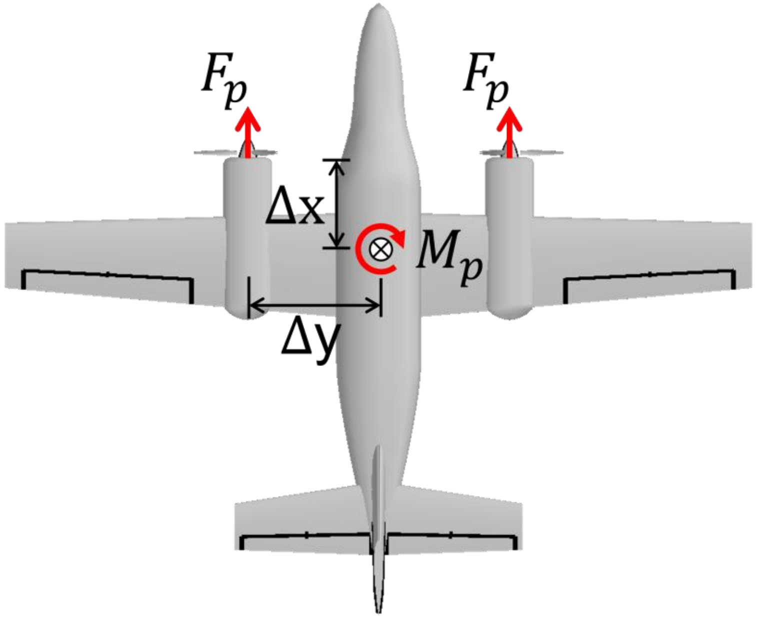
Force and Moment Models

Ground Forces



- Simple force balance
- Zero sum of moments

Propulsion



- Offset from CG
- Moments from CLOT

Force and Moment Models

Landing Gear

$$N = W + F_{z_f}$$
$$F_\mu = \mu N$$

Takeoff	Landing
$\mu = 0.03$	$\mu = 0.4$

$$M_{gear} = -(M_{thrust} + M_{aero})$$

Propulsion

Nominal

$$\begin{bmatrix} F_{x_p} \\ F_{y_p} \\ F_{z_p} \\ M_{x_p} \\ M_{y_p} \\ M_{z_p} \end{bmatrix} = \begin{bmatrix} T\cos(\alpha_t) \\ 0.0 \\ -T\sin(\alpha_t) \\ 0.0 \\ T[\Delta z\cos(\alpha_t) + \Delta x\sin(\alpha_t)] \\ 0.0 \end{bmatrix}$$

One Engine Inoperative

$$\begin{bmatrix} F_{x_p} \\ F_{y_p} \\ F_{z_p} \\ M_{x_p} \\ M_{y_p} \\ M_{z_p} \end{bmatrix} = \begin{bmatrix} 0.5T\cos(\alpha_t) \\ 0.0 \\ -0.5T\sin(\alpha_t) \\ 0.5T\sin(\alpha_t)\,\Delta y \\ 0.5T[\Delta z\cos(\alpha_t) + \Delta x\sin(\alpha_t)] \\ 0.5T\cos(\alpha_t)\Delta y \end{bmatrix}$$