Air Force Research Laboratory

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Verification Challenges in F-16 Ground Collision Avoidance and Other Automated Maneuvers (Benchmark Proposal)

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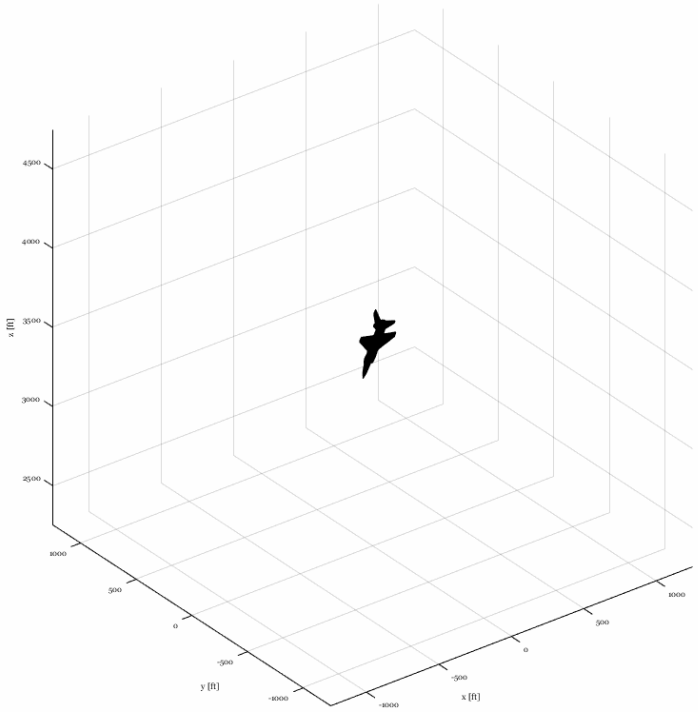
Motivation

t = 0.00 sec Waiting
h = 3500.00 ft V = 540.00 ft/s
α = 2.12 deg β = 0.00 deg
N_z = 0.17 g p_s = 0.00 deg/s
[ϕ θ ψ] = [45.0, -72.0, -45.0] deg



The Big Picture

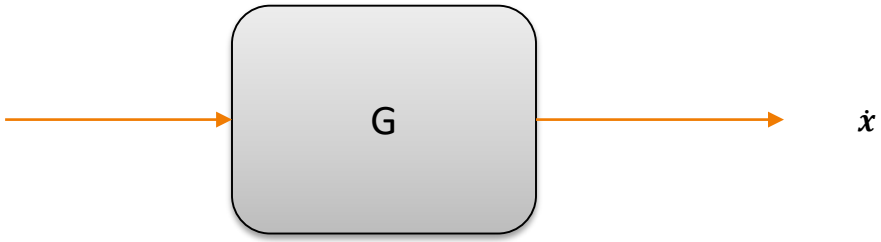
- What is this model?
  - Nonlinear model of F-16 (with lookup tables, control saturation)
  - Stabilizing linear controller designed at single trim point
  - Basic autopilot with discrete & continuous logic
    - Speed control
    - Altitude hold
    - Ground collision avoidance maneuver
    - Track to waypoint
  - Automatic Pass/Fail tests with optional visualizations
- Where is it available?
  - https://github.com/pheidlauf/aerobenchvv [MATLAB]
  - https://github.com/stanleybak/AeroBenchVVPython

Aircraft Model

$$\boldsymbol{x} = \begin{bmatrix} V \\ \alpha \\ \beta \\ \phi \\ \theta \\ \psi \\ P \\ Q \\ R \\ p_n \\ p_e \\ h \\ \text{pow} \\ \int \begin{pmatrix} N_{z_e} \\ P_{s_e} \\ (N_y + r)_e \end{pmatrix} \end{bmatrix}$$

$$\boldsymbol{u_{F16}} = \begin{bmatrix} \delta_t \\ \delta_e \\ \delta_a \\ \delta_r \end{bmatrix}$$

Standard Aerospace Engineering Nonlinear Model



Stevens & Lewis

State & Control Definitions

State Vector (extended)

$\boldsymbol{x} =$	V	Airspeed	(ft/s)
	α	Angle of attack	(rad)
	β	Angle of sideslip	(rad)
	ϕ	Roll angle	(rad)
	θ	Pitch angle	(rad)
	ψ	Yaw angle	(rad)
	P	Roll rate	(rad/s)
	Q	Pitch rate	(rad/s)
	R	Yaw rate	(rad/s)
	p_n	Northward displacement	(ft)
	p_e	Eastward displacement	(ft)
	h	Altitude	(ft)
	pow	Engine thrust	(lbf)
	$\int \begin{pmatrix} N_{z_e} \\ P_{s_e} \\ (N_y+r)_e \end{pmatrix}$	Integral of down force error	(g's)
		Int of stability roll rate error	(rad)
		Int of side force & yaw rate error	(mixed)

Control Vector (Inner Loop)

$\boldsymbol{u}_{F16} =$	δ_t	Throttle	(%)
	δ_e	Elevator	(rad)
	δ_a	Aileron	(rad)
	δ_r	Rudder	(rad)

Reference Input (Outer Loop)

$\boldsymbol{u}_{out} =$	N_z	Down force	(g's)
	P_s	Stability roll rate	(rad/s)
	$N_y + r$	Side force & yaw rate	(mixed)

Aircraft Model & Decoupling

Longitudinal Dynamics

N_z is the downward g-force felt by the pilot. N_z

P_s is the stability roll rate (roll rate about the velocity vector) P_s

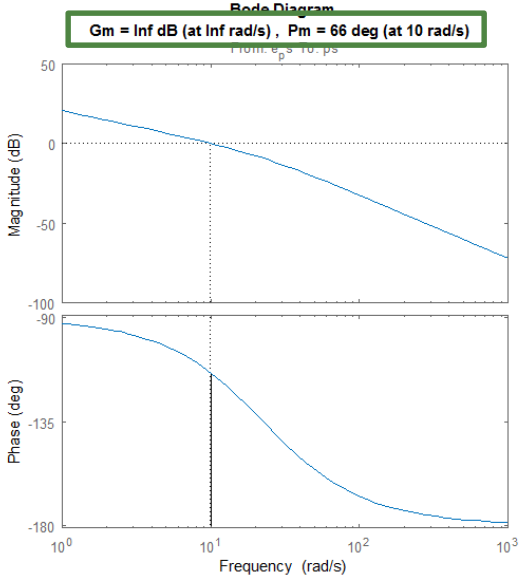
Lateral Dynamics

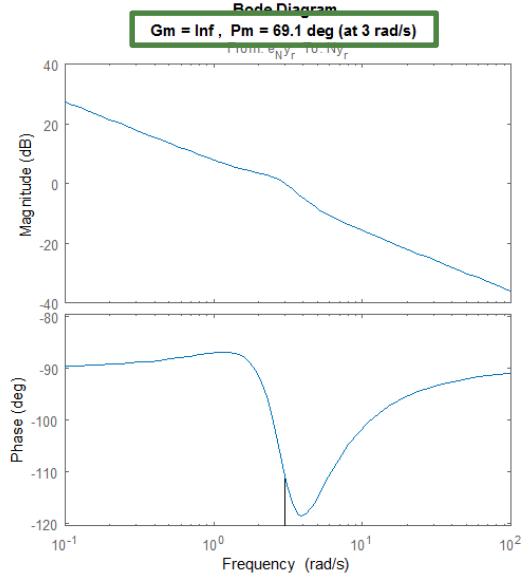
N_y + [illegible] of the side force and yaw rate (undesirable)

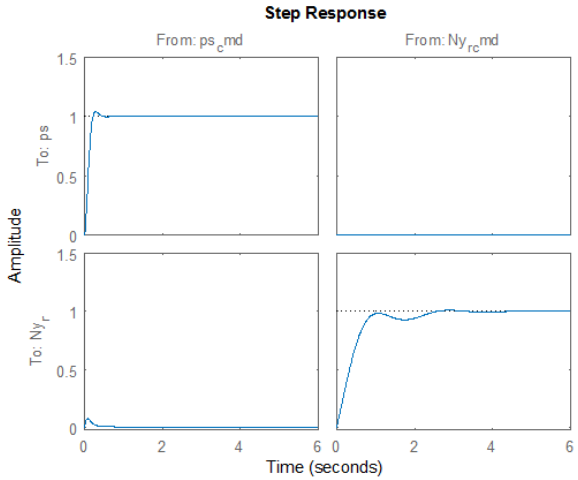
$N_y + r$

Tuning of LQR Controller

- Controller is tuned to yield pilot-preferred responses
- Good gain and phase margins at the desired gain crossover frequencies
- Good decoupling between P_s and $N_y + r$

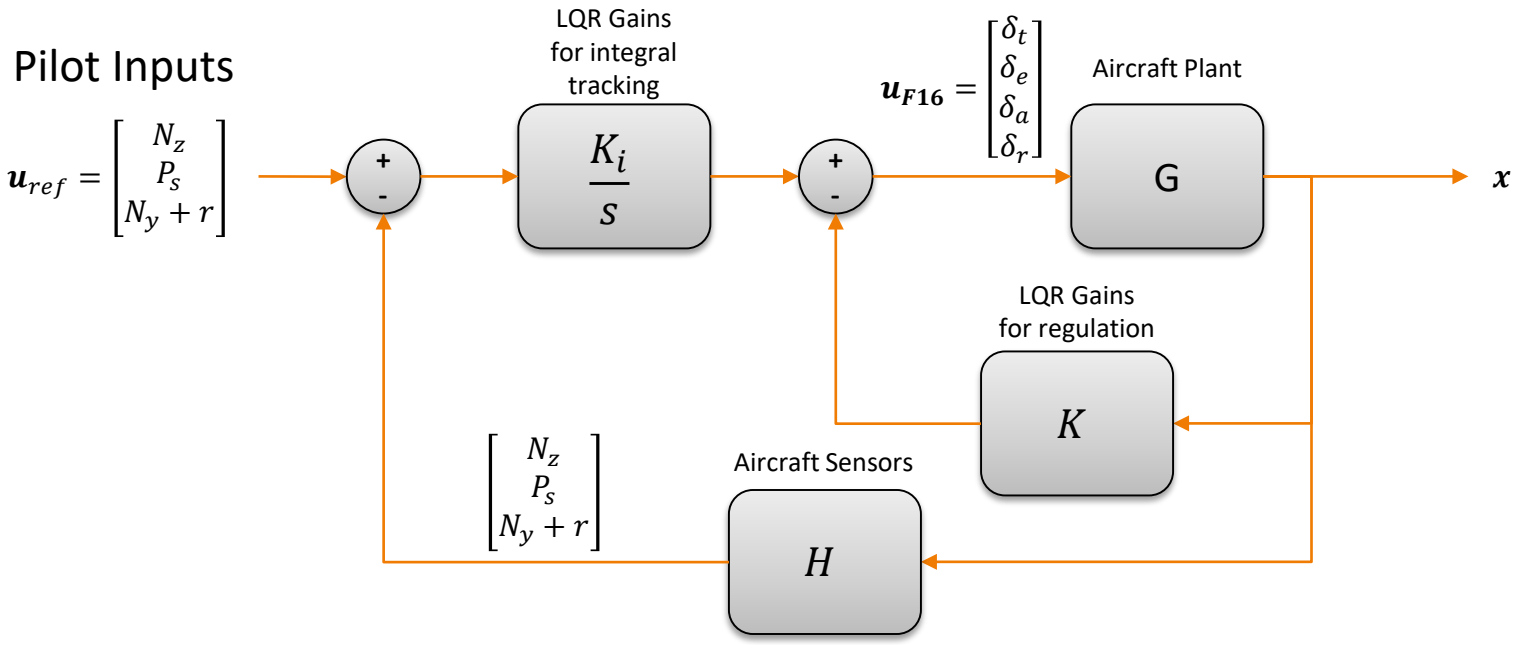






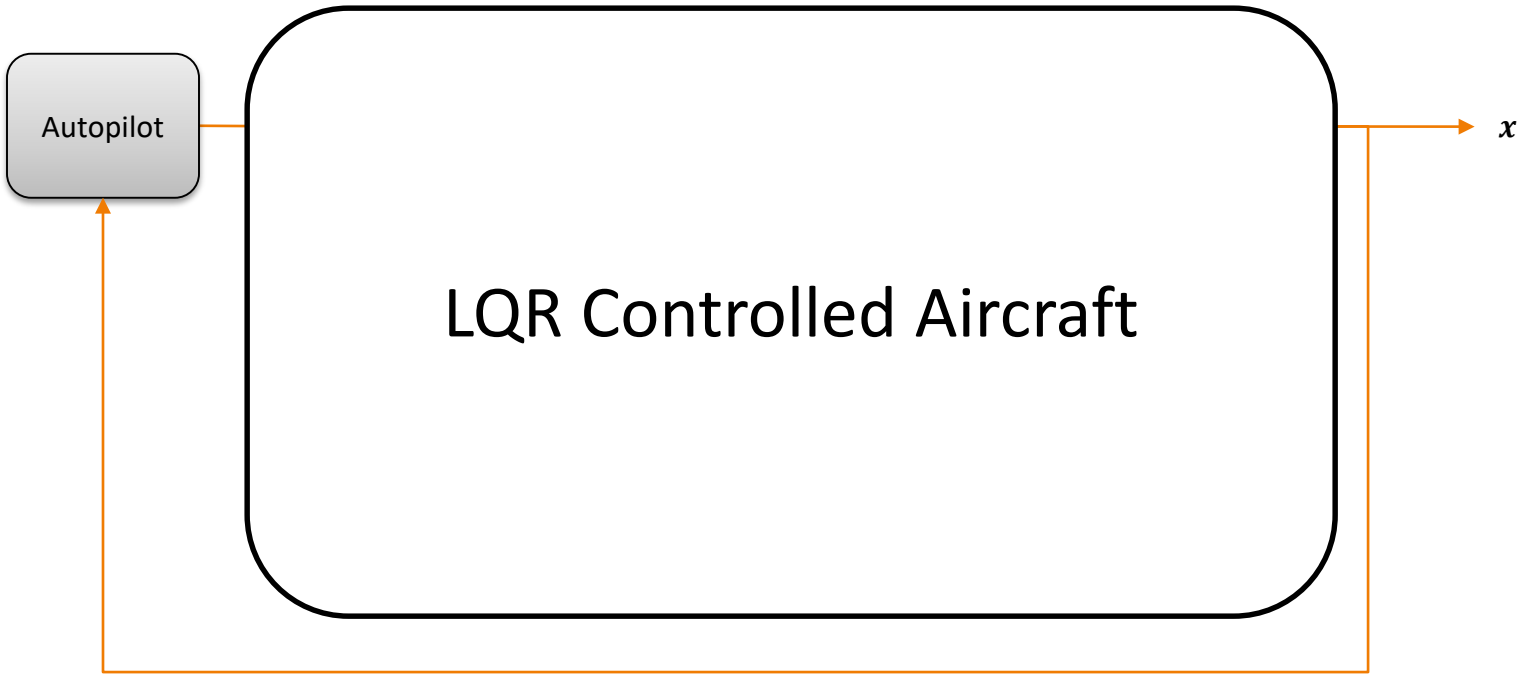
Lateral Dynamics & Control

Inner Loop Control Architecture



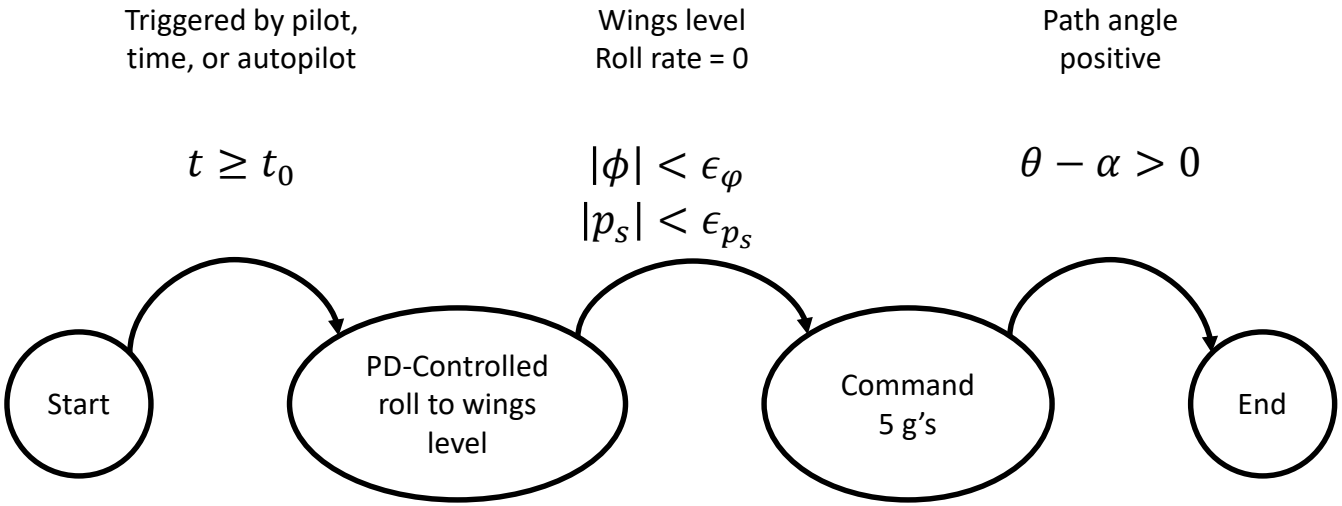
Continuous dynamics

Outer Loop Control Architecture



Continuous & Discrete Dynamics

Outer Loop Control Subroutines



Continuous & Discrete Dynamics

Sample Pass / Fail Specifications

If V, α, or β exceed the aircraft limits, the aircraft has “diverged” or flown out of control

$$300\ \frac{ft}{sec} < V < 900\ \frac{ft}{sec}$$
$$-10° < \alpha < 40°$$
$$-30° < \beta < 30°$$

If the maneuver is too extreme, then the aircraft is overstressed

$$-2\ \mathrm{g} < N_z < 9\ \mathrm{g}$$

If the aircraft flies too low, then the aircraft crashes

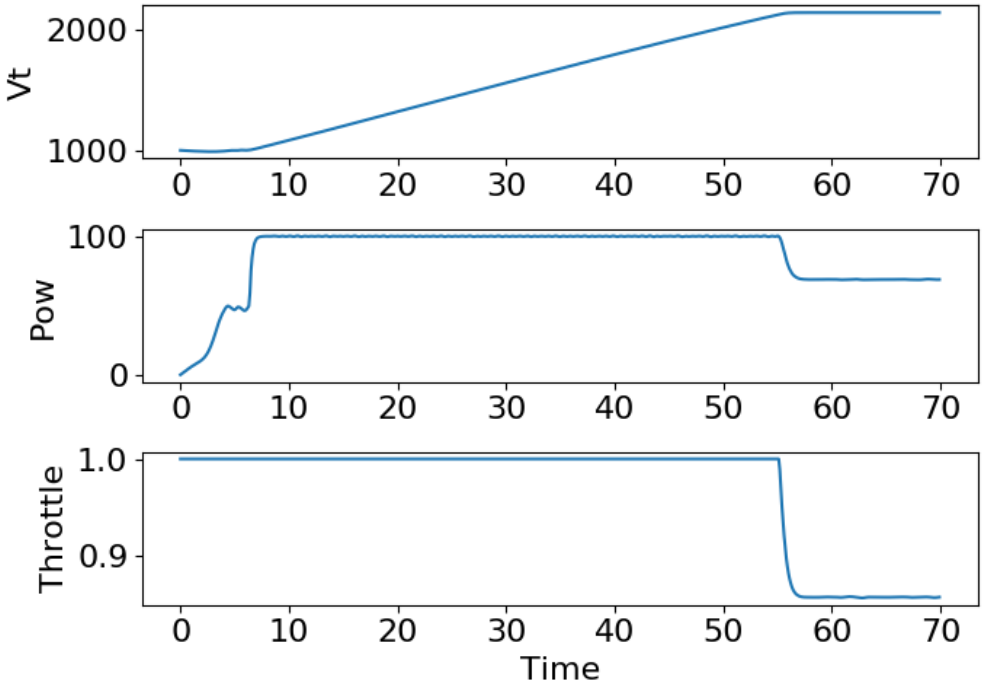
$$h \geq h_{min}$$

If the maneuver takes too long, then the time specification is violated

$$t_f - t_i > t_{max}$$

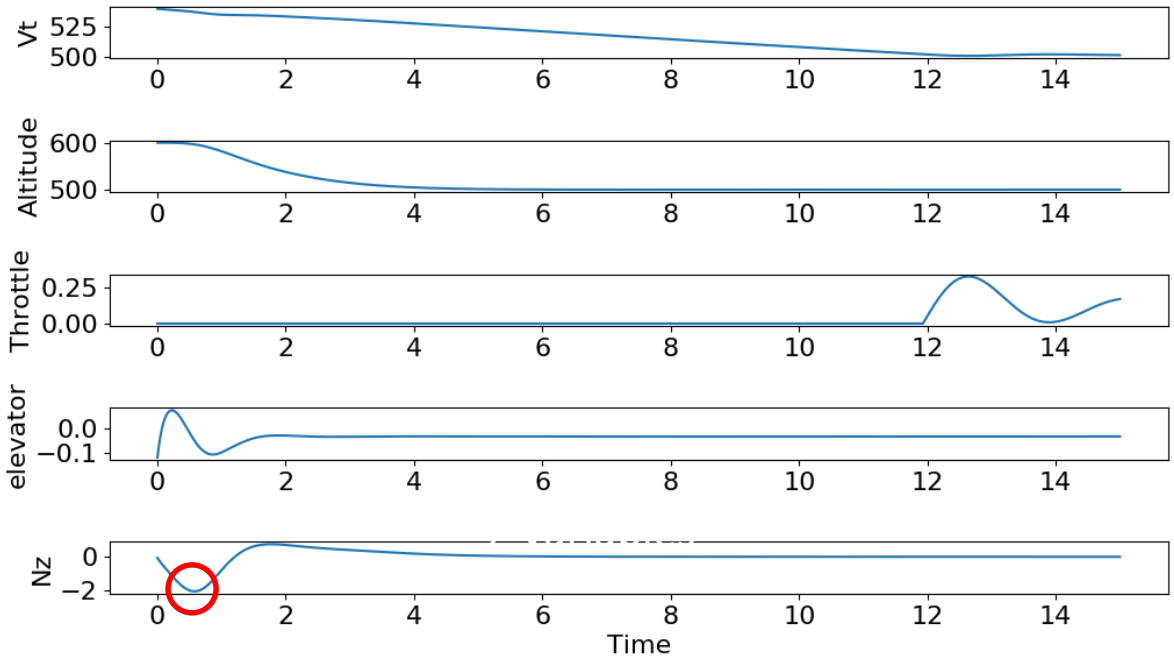
Easy: Engine Control

Case	Initial Altitude `alt` (ft)	Initial Speed `Vt` (ft/sec)	Setpoint `sp` (ft/sec)
1A	10000	1000	[1200, 1220]
1B	10000	1100	[1200, 1220]
1C	10000	[1000, 1100]	[1200, 1220]
1D	[10000, 11000]	[1000, 1100]	[1200, 1220]
1E	20000	1000	[2200, 2220]
1F	40000	1000	[2200, 2220]
1G	[20000, 40000]	1000	[2200, 2220]
1H	[5000, 30000]	[1000, 2000]	[1000, 2000]

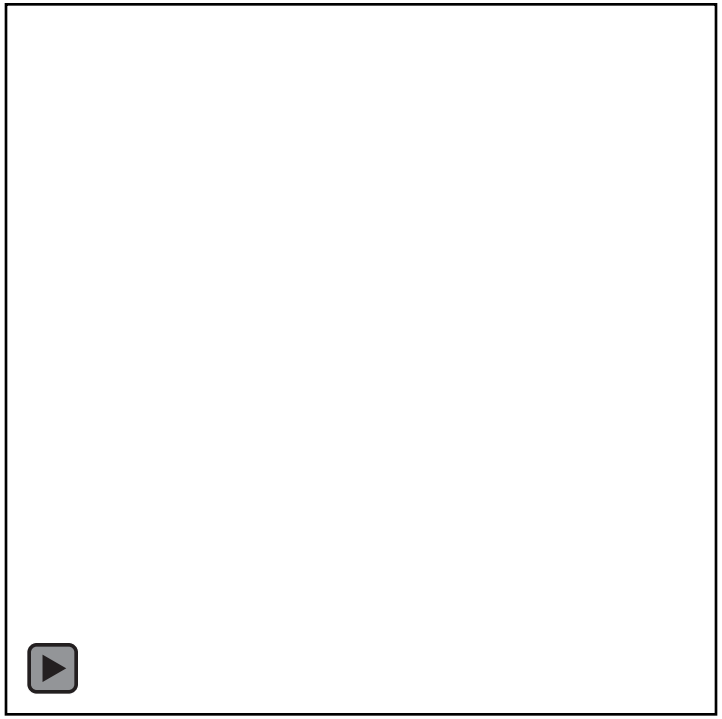


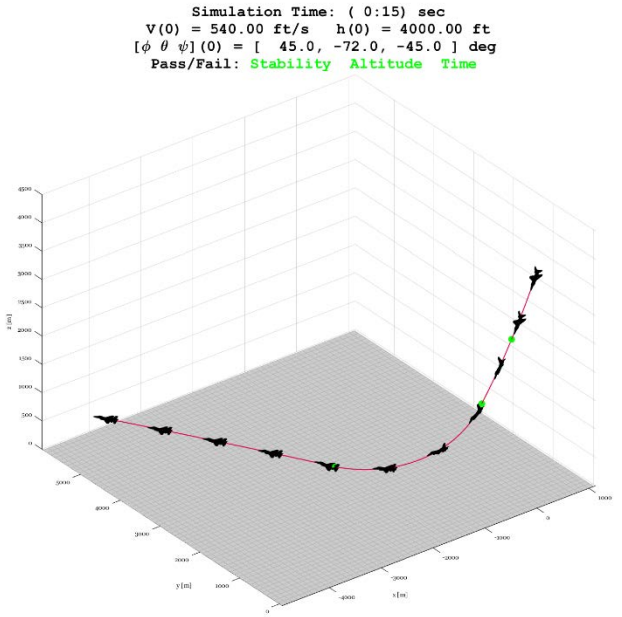
Medium: Longitudinal Control

Case	Initial States
2A-2H	Same as 1A-1H using the airspeed controller and specs
2I	`Vt` = 560, `alt` = [550, 560], `sp`=500
2J	`Vt` = 560, `alt` = [590, 600], `sp`=[500, 505]
2K	`Vt` = [560, 600], `alt` = [590, 600], `sp`=[500, 505]
2L	`Vt` = [560, 500], `alt` = [600, 500], `sp`=[700, 800]
2M-2P	Same as 2I-2L with $\alpha = [-0.1, 0.1]$, $\theta = \alpha$, `Q` = [-0.1, 0.1]

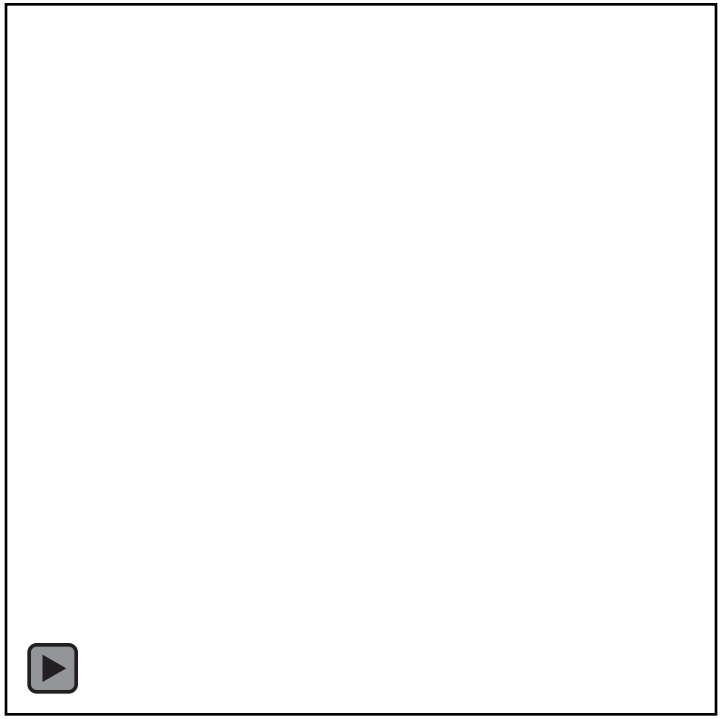


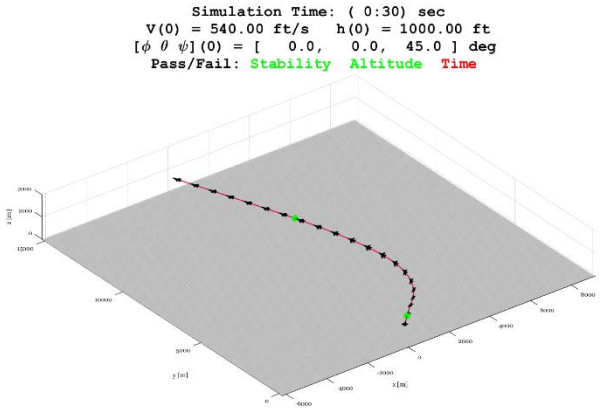
Hard: Ground Collision Avoidance





Extra: Track to Waypoint





https://github.com/pheidlauf/aerobenchvv

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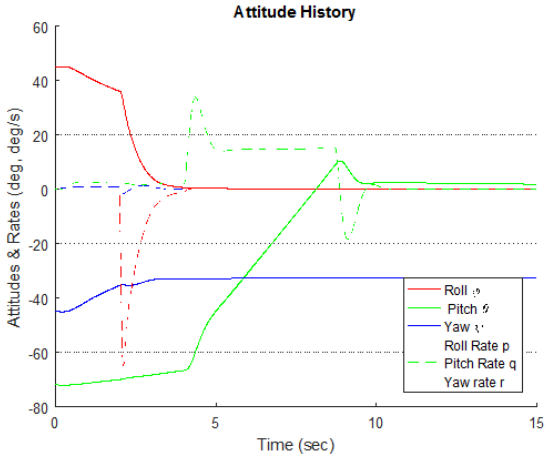

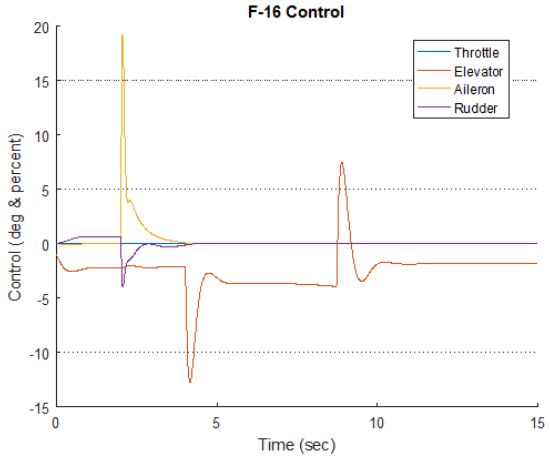

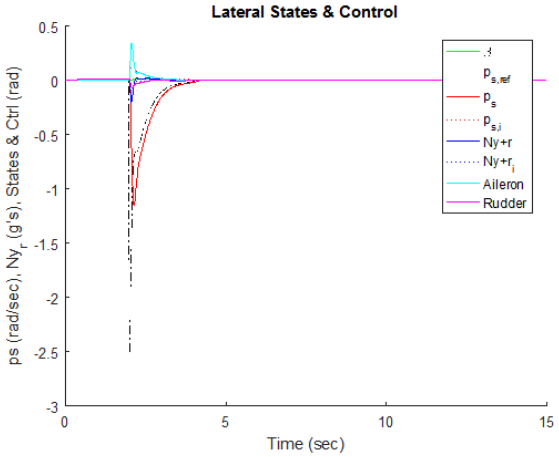

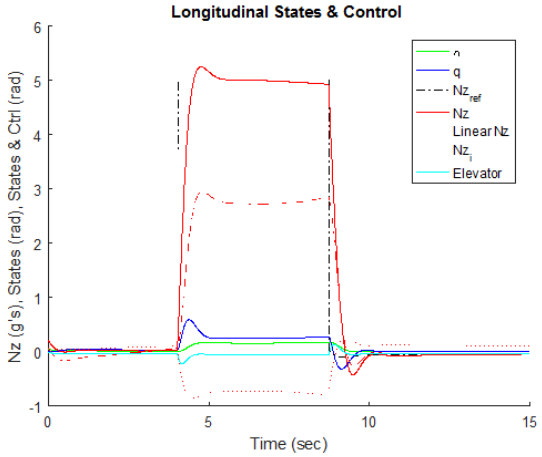

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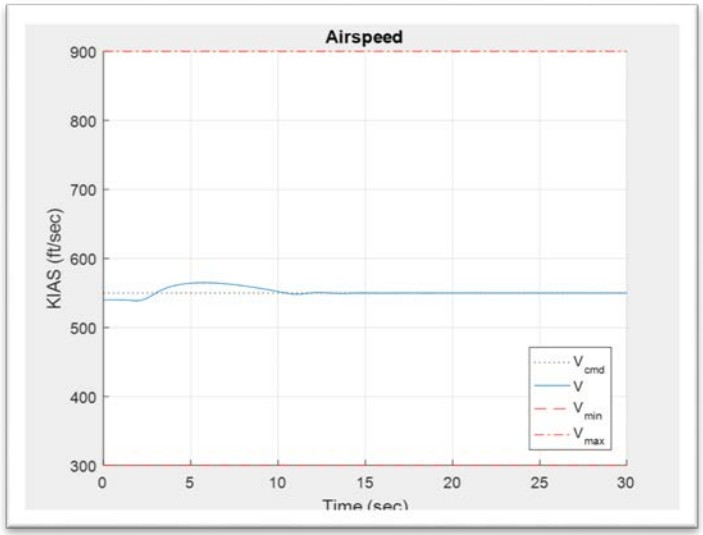

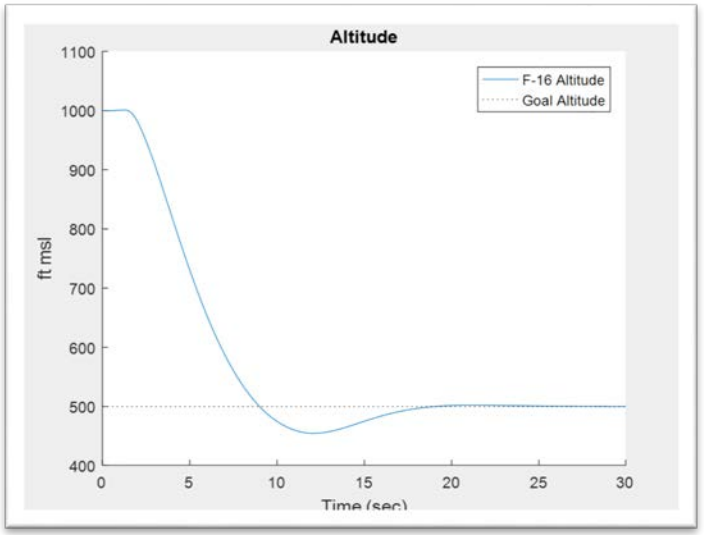

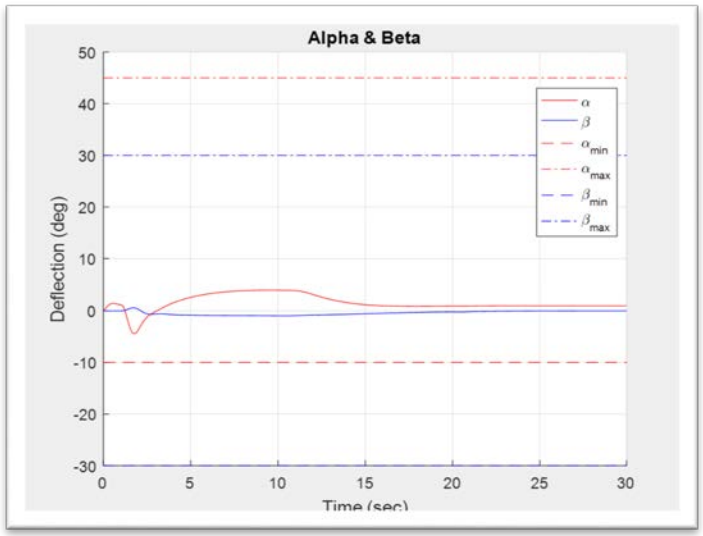

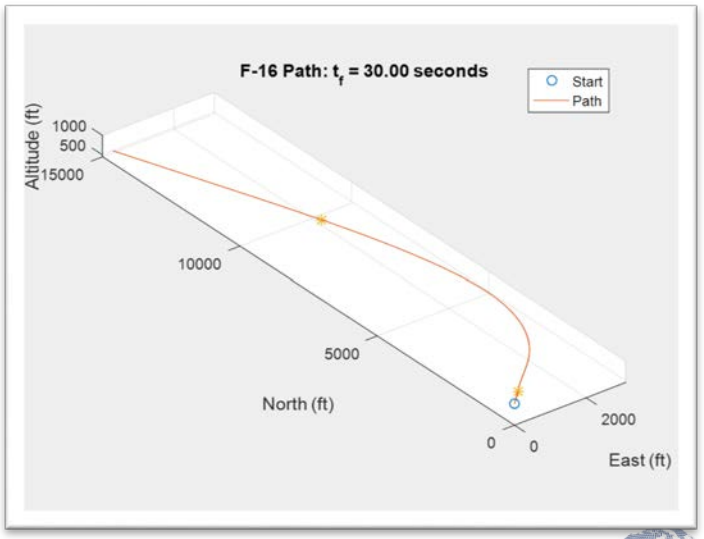

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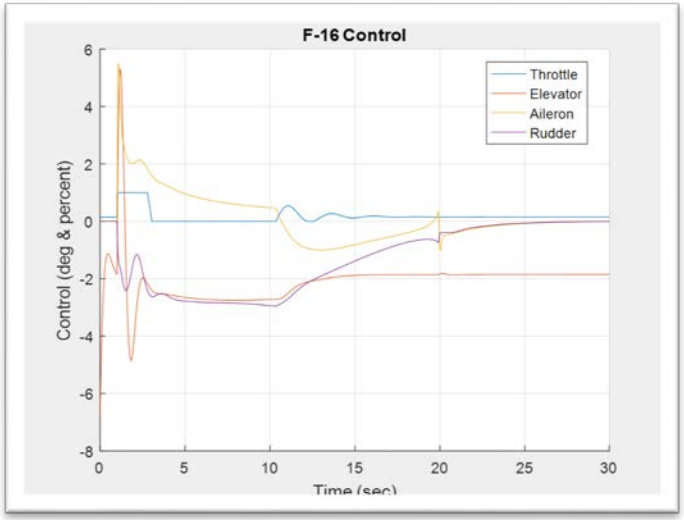

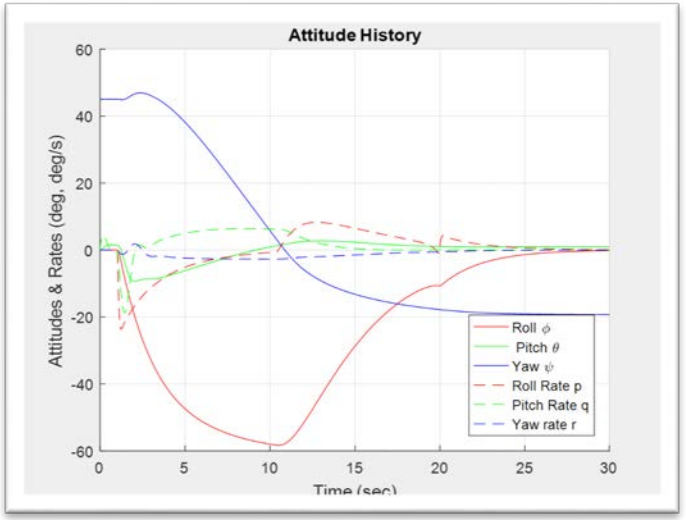

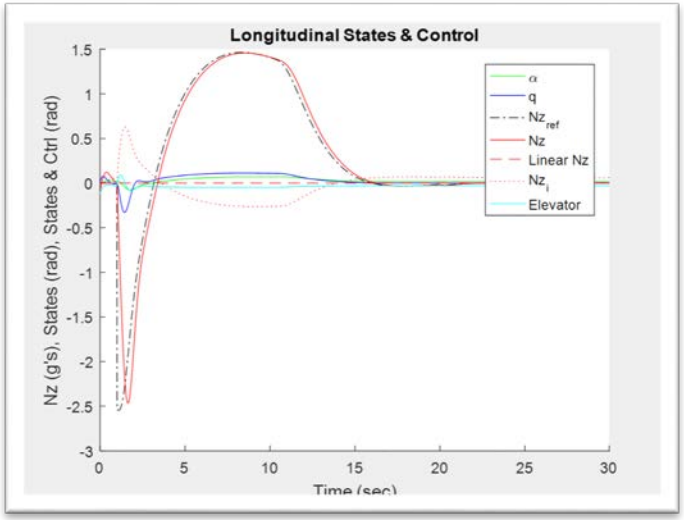

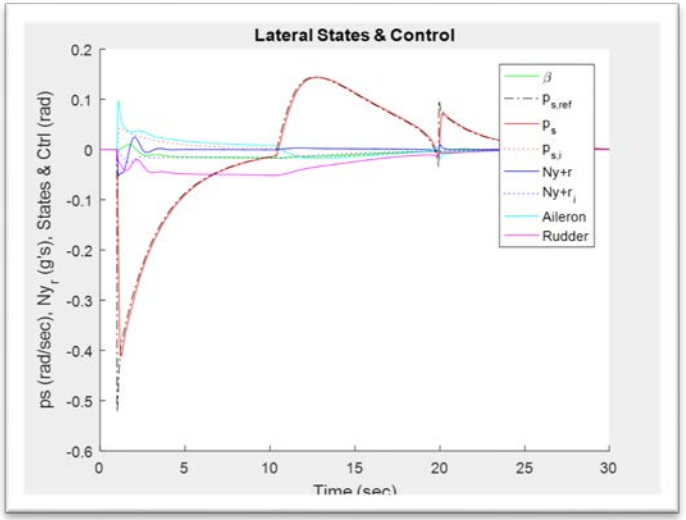

Motivation

http://aviationweek.com/air-combat-safety/auto-gcas-saves-unconscious-f-16-pilot-declassified-usaf-footage

https://www.youtube.com/watch?v=WkZGL7RQBVw