Robust and Resilient Autonomy for Advanced Air Mobility

NASA Aeronautics Mission Directorate
University Leadership Initiative
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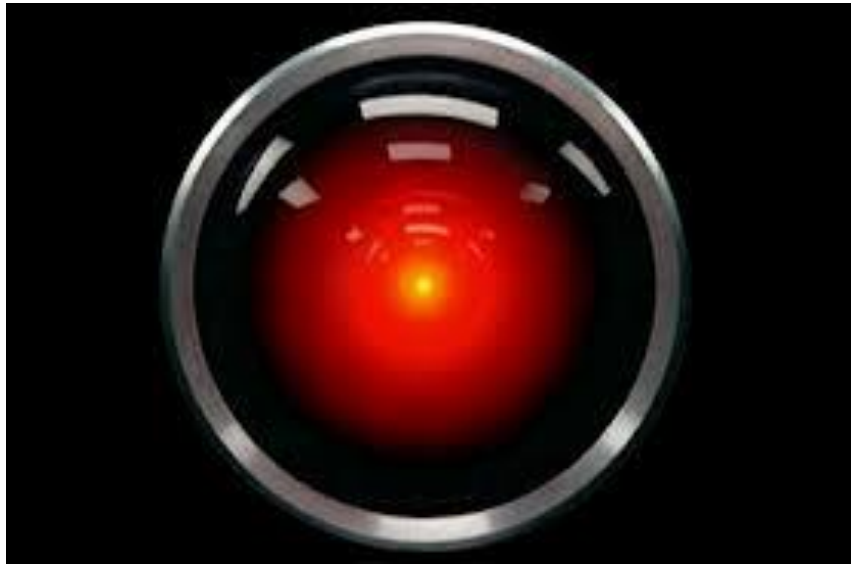
NASA | AVIATE CENTER | University of Illinois Urbana-Champaign | Massachusetts Institute of Technology | Georgia Tech | North Carolina Agricultural and Technical State University | University of Nevada, Reno | Lockheed Martin | Sierra Nevada Corporation

PRELIMINARIES

- What is Autonomous Control?
  - Synonyms of Autonomous
    - freed, independent, individualistic, liberated, self-directing, self-ruling, separate, self-governing
  - Wikipedia
    - Ancient Greek: Auto “self”, nomos “law”
      - “One Who Gives Oneself Their Own Law”
    - Robotics: “independence of control”



HAL 9000 [Ref 2001]

PRELIMINARIES

- **Briefs Concept of Ten Degrees of Autonomy [How, MIT]**
  - **0: Remotely Piloted**
  - **1: Remotely Guided**
  - **2: Real Time Health Diagnosis & Action**
  - **3: Adapt to Uncertainty & Failures**
  - **4: Onboard Route Replan**
  - **5: Group Coordination**
  - **6: Group Tactical Replan**
  - **7: Group Tactical Goals**
  - **8: Distributed Control (Non-Centralized)**
  - **9: Group Strategic Goals**
  - **10: Fully Autonomous (No Humans ITL)**

PRELIMINARIES

- **Briefs Concept of Ten Degrees of Autonomy [How, MIT]**
  - **0: Remotely Piloted**
  - **1: Remotely Guided**

  } **Tier 1, Basic Navigational Autonomy**

  - **2: Real Time Health Diagnosis & Action**
  - **3: Adapt to Uncertainty & Failures**
  - **4: Onboard Route Replan**

  } **Tier 2, Self Govern**

  - **5: Group Coordination**
  - **6: Group Tactical Replan**
  - **7: Group Tactical Goals**

  } **Tier 3, Multi-Agent Autonomy**

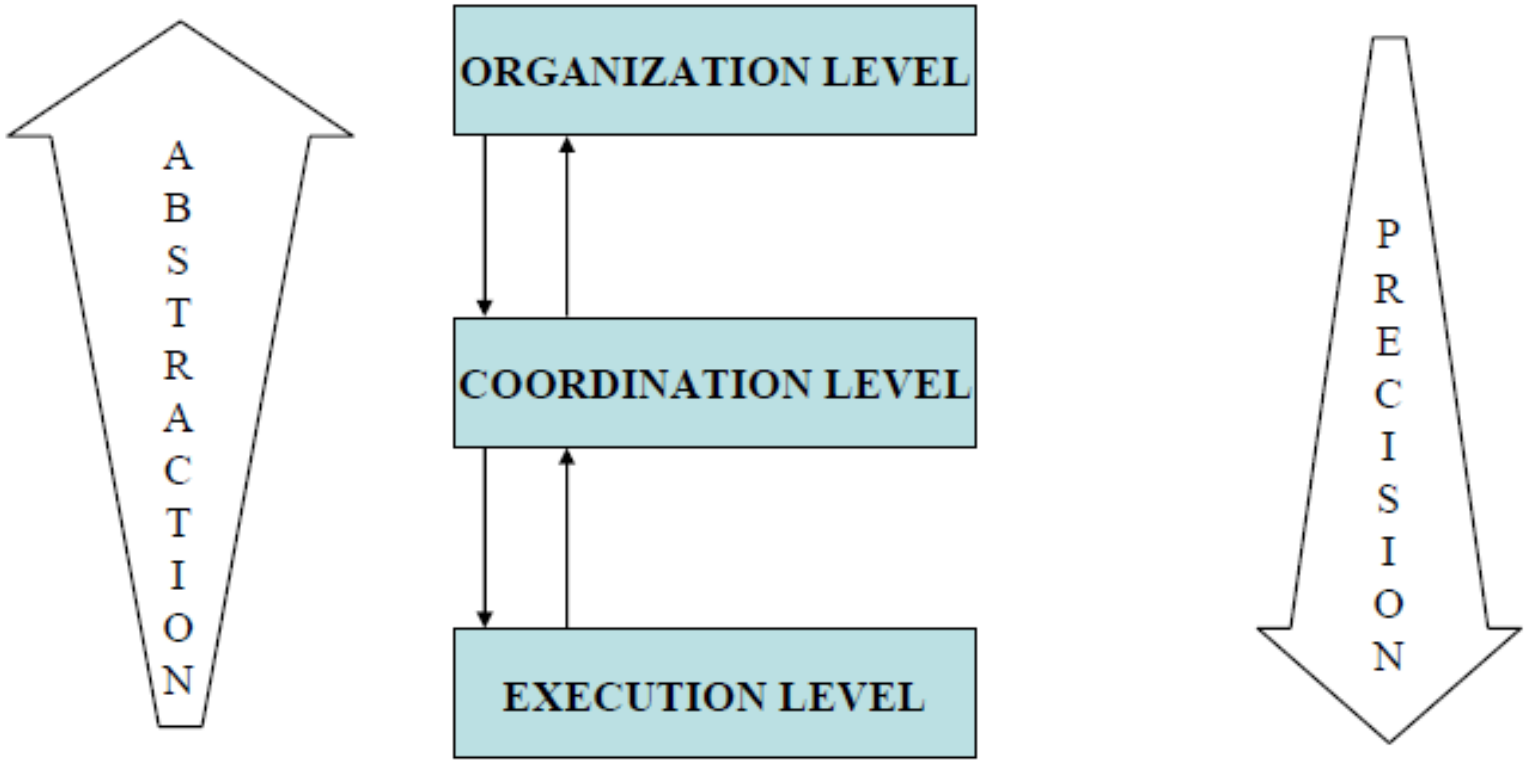
  - **8: Distributed Control (Non-Centralized)**
  - **9: Group Strategic Goals**
  - **10: Fully Autonomous (No Humans ITL)**

  } **Tier 4, Advanced Autonomy**

Clearly, Autonomous Systems Require Multiple Elements → Controllers, Sensors, Machine Learning Algorithms…

PRELIMINARIES

Saridis



THREE-LAYER PLANNING AND CONTROL ARCHITECTURE

PRELIMINARIES

- **Ciccarelli and Letunic Consensus of Species**

- **4 Billion Year Old Timeline in 40 Seconds – Carl Sagan, http://www.youtube.com/watch?v=5g2crxb-PJs**

Dr. Carl Sagan
1934 – 1996

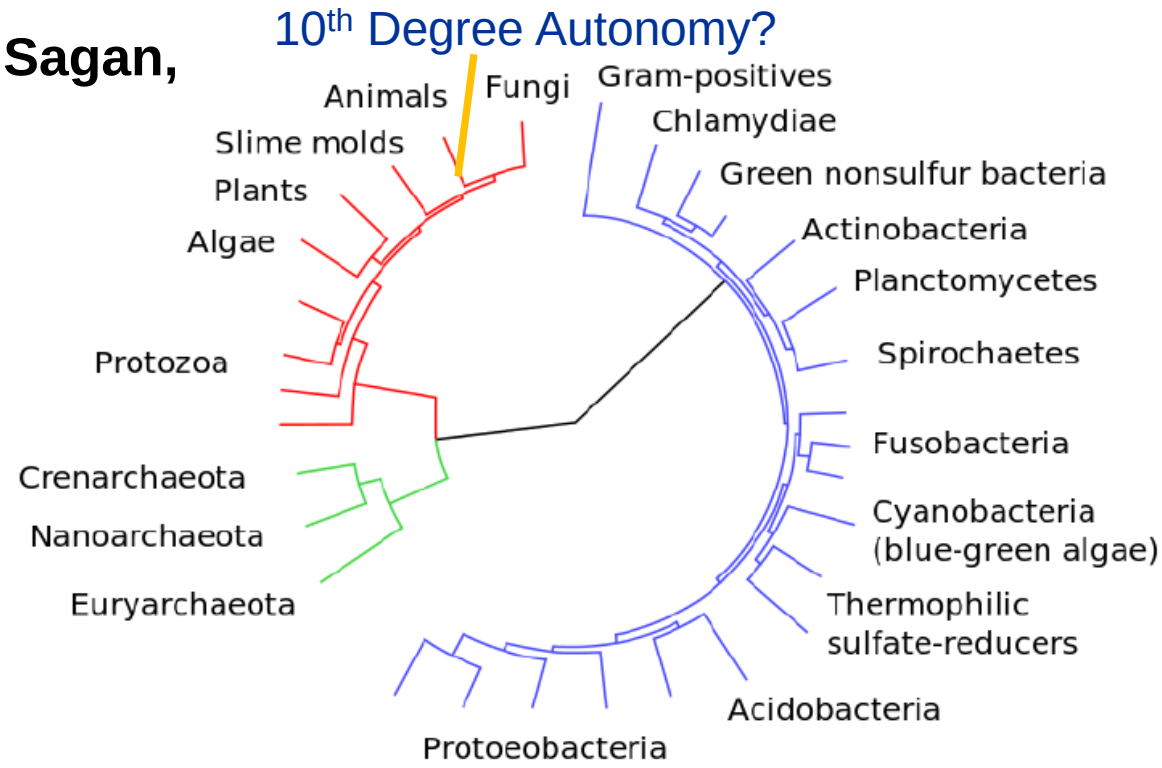


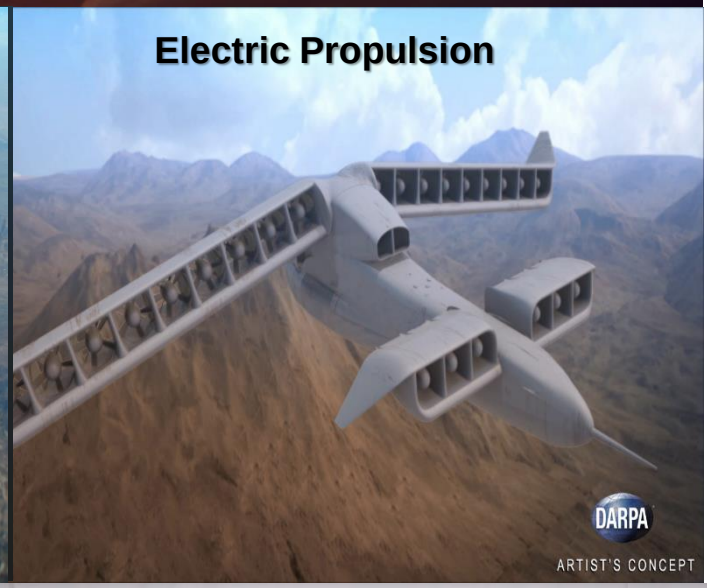
Fig. 1. The "Tree of Life" is a Directed Spanning Tree [2].

Distributed Effectors

Tailless Fighters

Quiet Supersonic

Electric Propulsion



Hybrid Wing Body

Dynamic Multi-Agent Systems

Flight Test

Complex Dynamic System

System Identification and Maturation

Governing 1st Principles

Models and Nonlinear ODEs

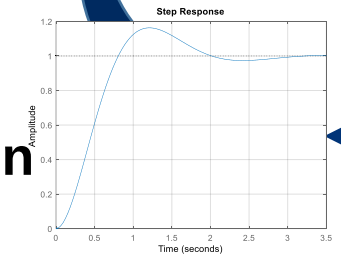
Integrated System Testi

Nonlinear Implementation

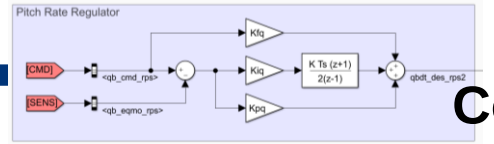
Linearization Approximation

Linear ODEs

$\mathcal{L}$ Transfer Functions



Time Domain Control Validation



Frequency Domain Control Design Realm

$\mathcal{L}^{-1}$

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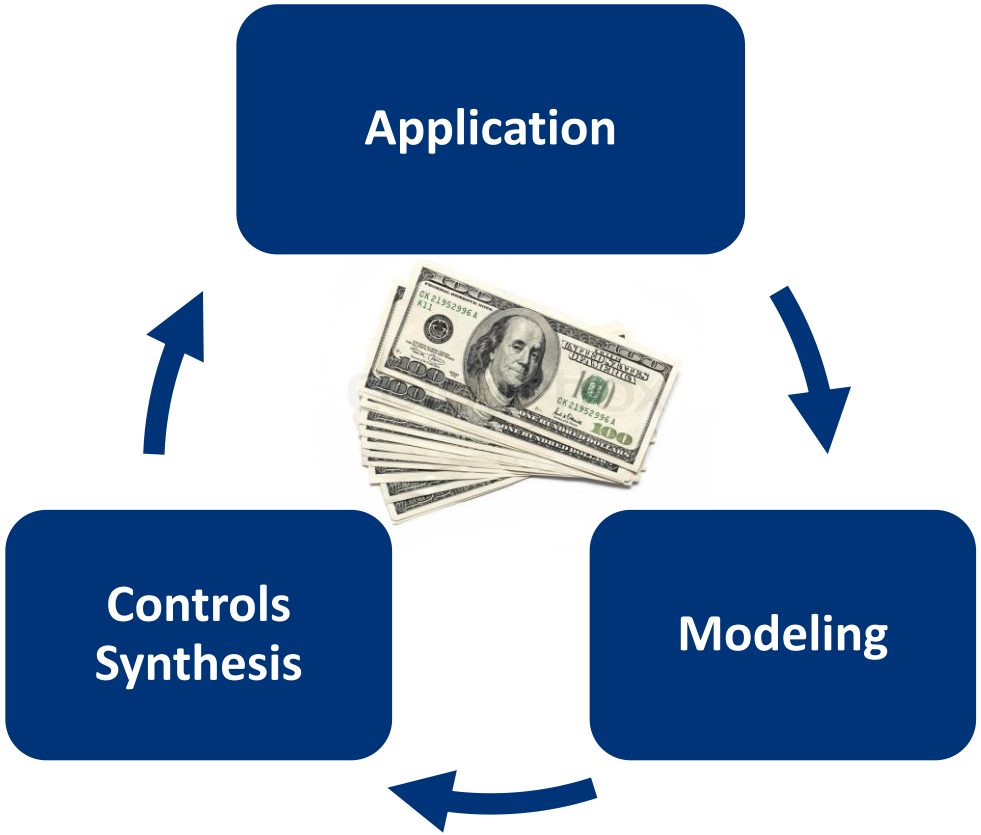
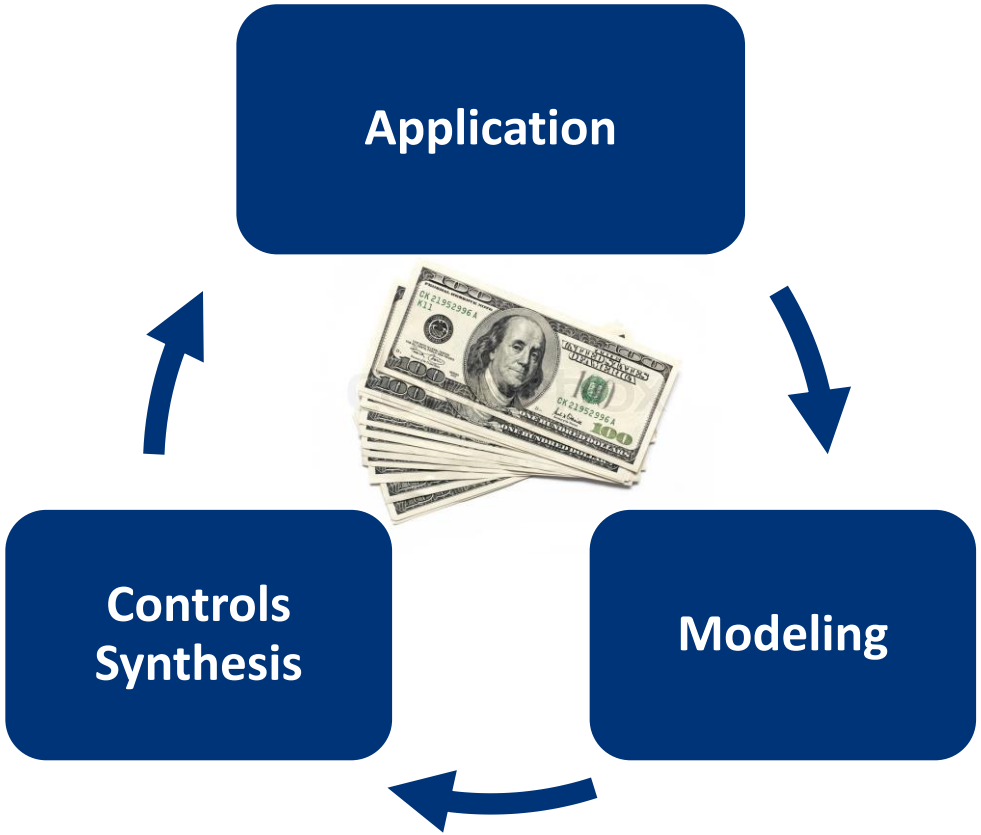
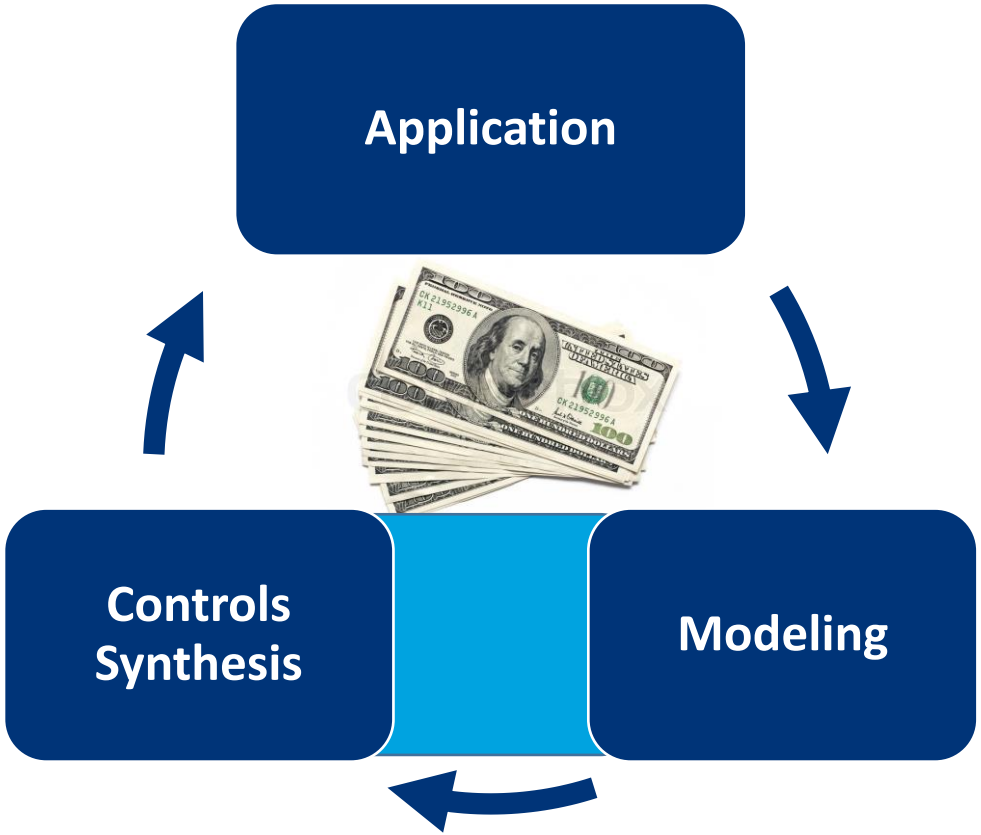




- **Flight Control Design**
  - **P-I-D, LQR, H_∞**
  - **Requires “Good” Models**
  - **Often iterative to “dial in”**



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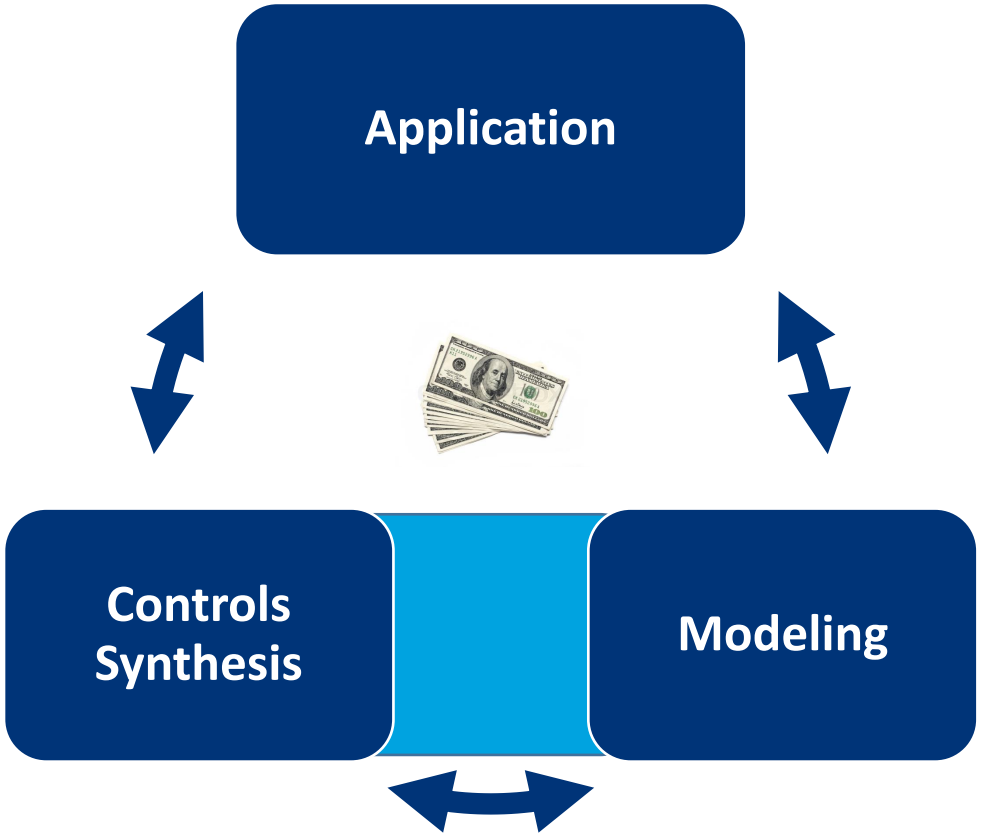
- **Model Reference Control (MRC)**
  - **I/O Feedback Linearization**
  - **Dynamic Inversion**
  - **Automated “Gain Scheduling”**



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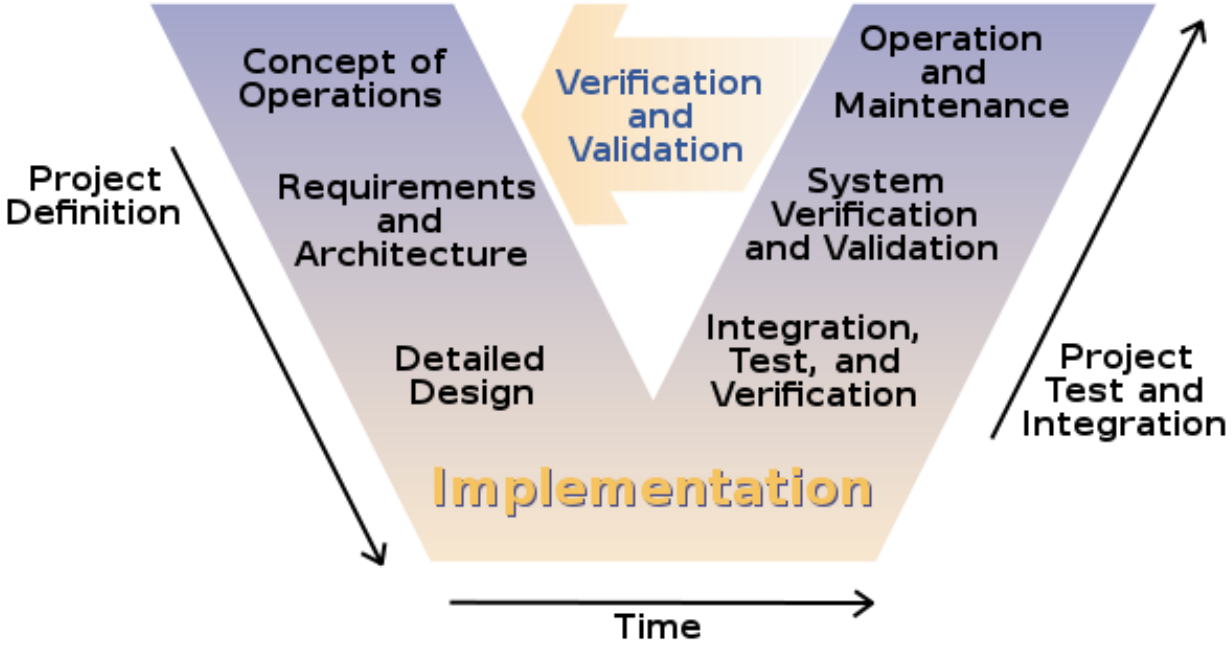
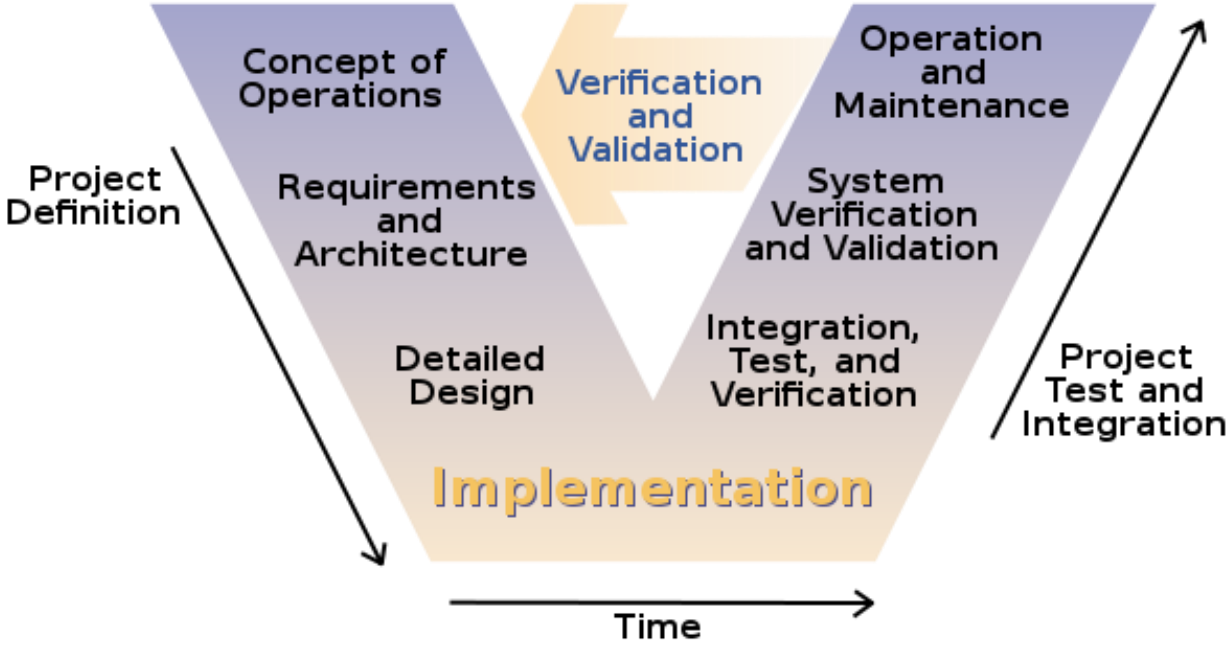
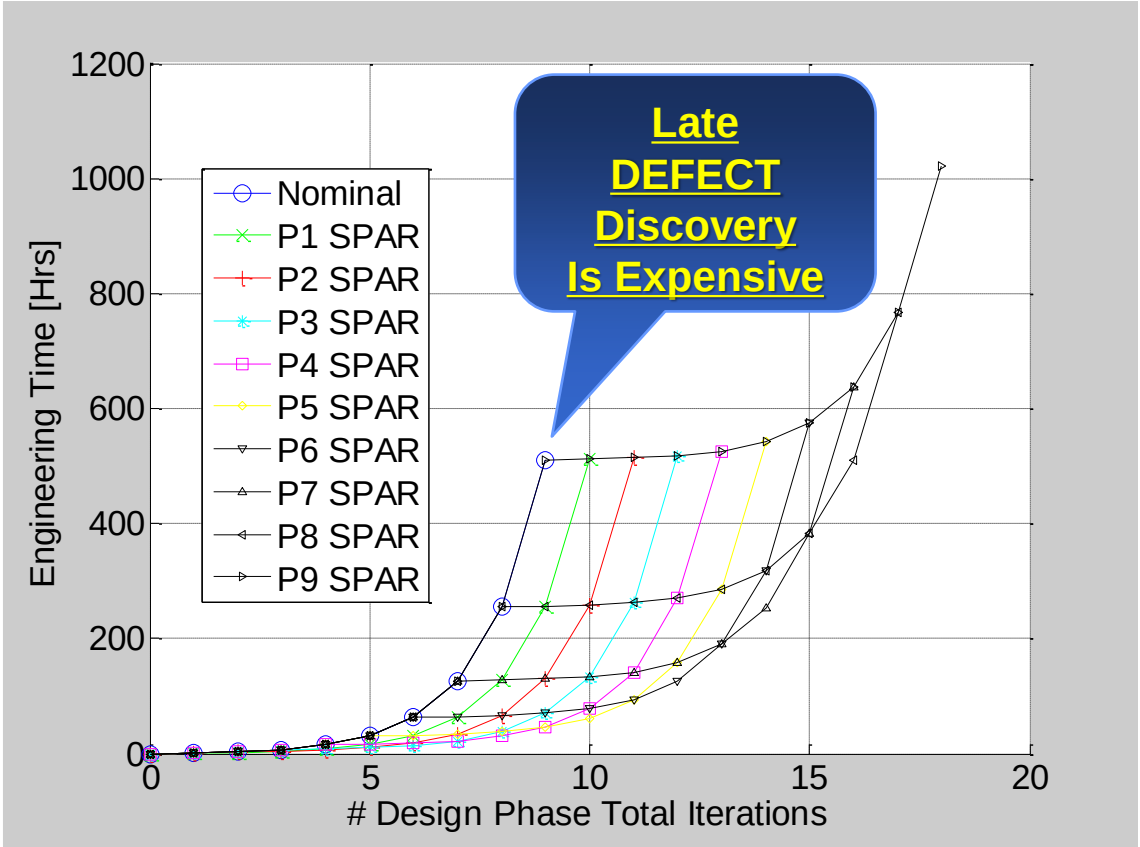
Future Systems Will Move from Inert MRC to Online MRAC

V&V



V&V





Traditional V&V Approach No Longer Viable for Tomorrow's System

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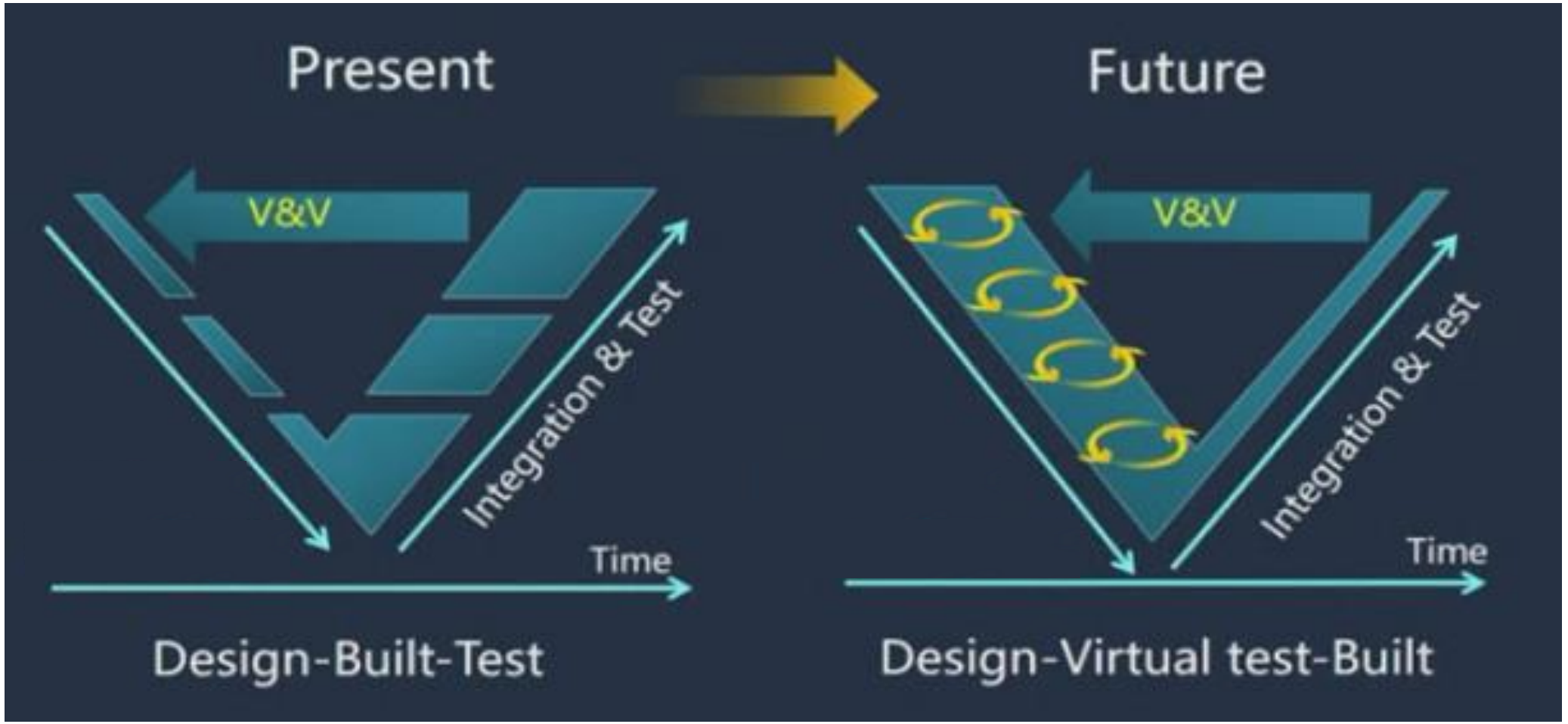
V&V



Integrated “Models” Needed to “Move Left” [Guo]

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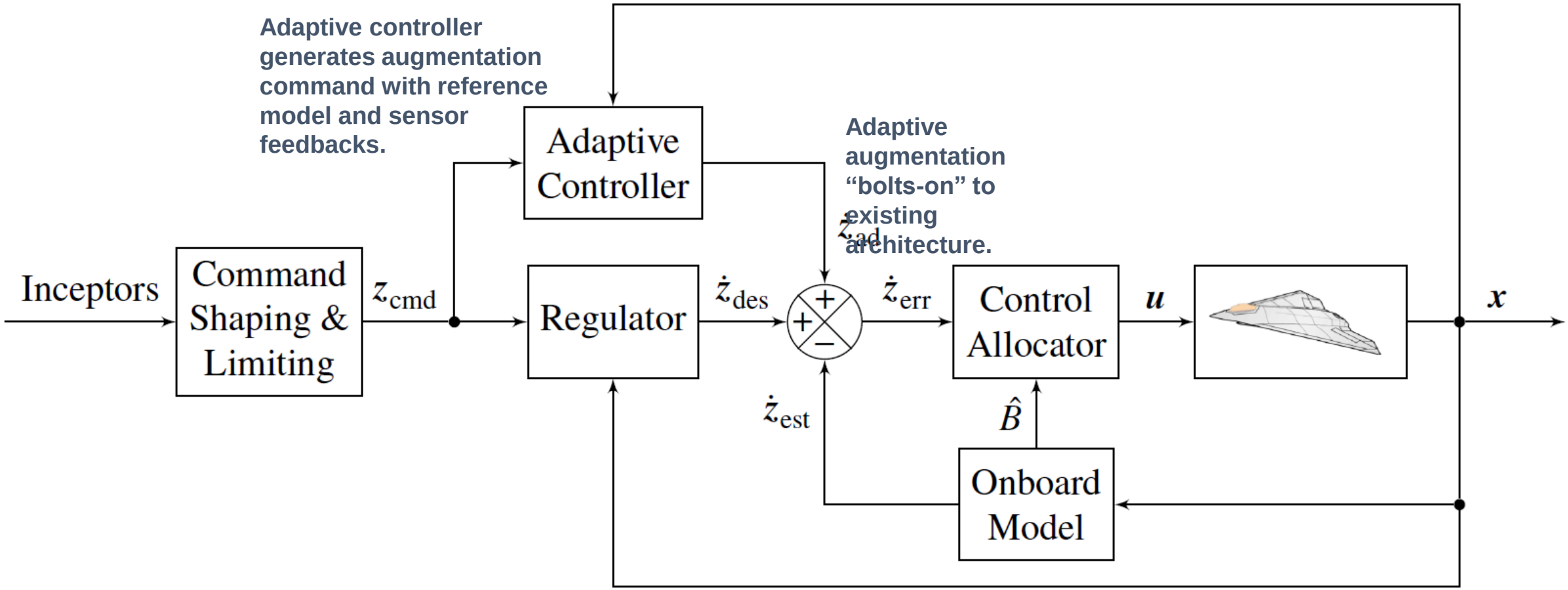
ADAPTIVE DYNAMIC INVERSION

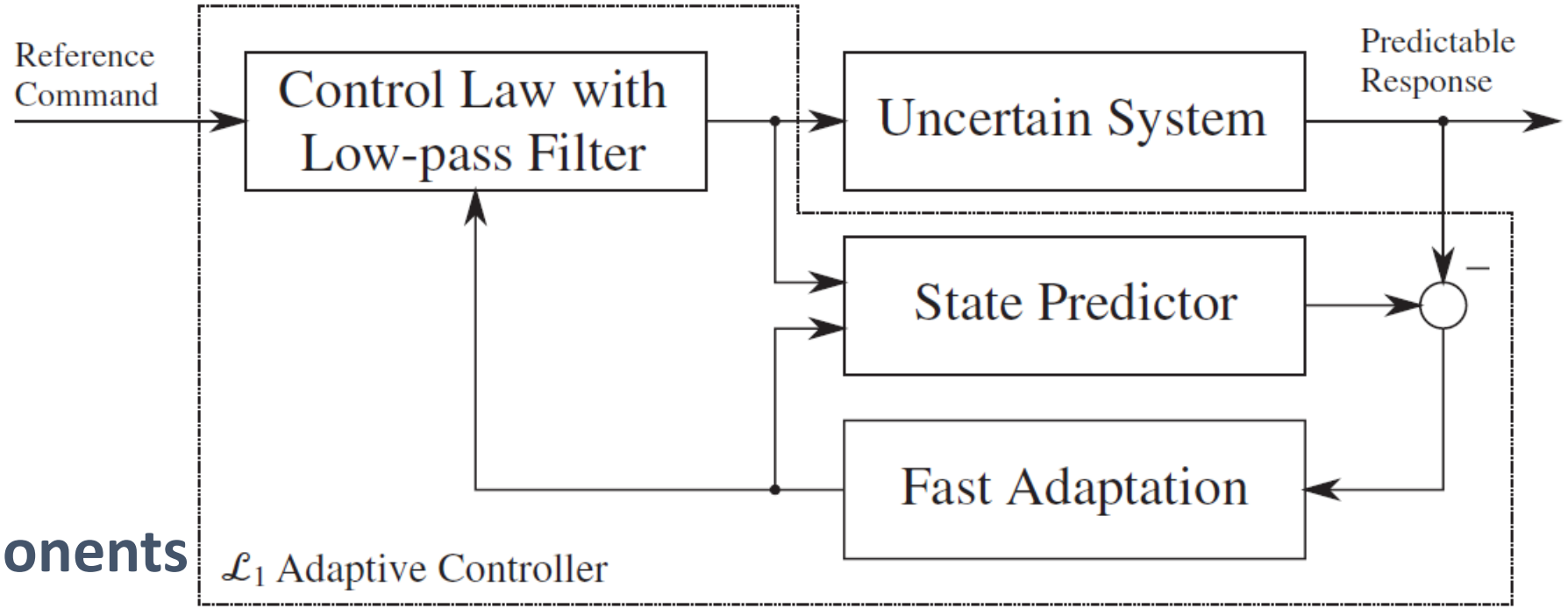
Adaptive controller generates augmentation command with reference model and sensor feedbacks.

Adaptive augmentation "bolts-on" to existing architecture.



RESEARCH INTO MRAC

[Hovakimyan & Cao]



Three major components

1. **Predictor (estimate system performance wrt desired)**
2. **mPC Adaptive Laws (ensures parameters remain bounded)**
3. **Control Law (low pass construct) prevents high freq adaptive signals to hardware**

$\mathcal{L}_1$ ADAPTIVE CONTROLLER

- **Substituting in the adaptive estimates of the state produces the state predictor:**

$$\dot{\hat{x}} = A_{\mathrm{m}}\hat{x} + B_{\mathrm{m}}\left(r + \dot{x}_{\mathrm{ad}} + \hat{\sigma}_{\mathrm{m}}(t)\right) + B_{\mathrm{um}}\hat{\sigma}_{\mathrm{um}}(t)$$

- **Adaptive laws (Li & Hovakimyan, 2012) :**

$$\begin{Bmatrix} \hat{\sigma}_{\mathrm{m}}(kT_{\mathrm{s}}) \\ \hat{\sigma}_{\mathrm{um}}(kT_{\mathrm{s}}) \end{Bmatrix} = [B_{\mathrm{m}} \quad B_{\mathrm{um}}]^{-1}\Phi^{-1}(T_{\mathrm{s}})\left(h(kT_{\mathrm{s}}) - \mu(kT_{\mathrm{s}})\right)$$

  - $\Phi(T_{\mathrm{s}}) = A_{\mathrm{m}}^{-1}\left(e^{A_{\mathrm{m}}T_{\mathrm{s}}} - I\right)$
  - $\mu(kT_{\mathrm{s}}) = e^{A_{\mathrm{m}}T_{\mathrm{s}}}\tilde{x}(kT_{\mathrm{s}});\ \tilde{x} = \hat{x} - x$

- **Modification Term:**

$$h(kT_{\mathrm{s}}) = h\left((k-1)T_{\mathrm{s}}\right) - \tilde{x}(kT_{\mathrm{s}})$$

- **Control Laws:**

$$\dot{x}_{\mathrm{ad}} = -C_1(s)\hat{\sigma}_{\mathrm{m}}(s) - C_2(s)H_{\mathrm{m}}^{-1}(s)H_{\mathrm{um}}(s)\hat{\sigma}_{\mathrm{um}}(s)$$

  - $H_{\mathrm{m}}(s) = C(sI - A_m)^{-1}B_{\mathrm{m}}$ **(minimum phase),** $H_{\mathrm{um}}(s) = C(sI - A_{\mathrm{m}})^{-1}B_{\mathrm{um}}$
  - $C_1(s)$ **strictly proper,** $C_2(s)$ **makes second term strictly proper**

Li, Z., and Hovakimyan, N., "L1 Adaptive Controller for MIMO Systems with Unmatched Uncertainties using Modified Piecewise Constant Adaptation Law," *51st IEEE Conference on Decision and Control*, IEEE, Maui, HI, 2012, pp. 7303–7308. doi:10.1109/CDC.2012.6425935.

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Partially Closed Loop Transfer Matrix with Adaption Off

Substitution into the controlled system output eq.2, the partially closed loop output (open loop adaptation) is then written as

$$\boldsymbol{Y_c}(s) = \boldsymbol{H_o x(0^-)} + \boldsymbol{H_R R}(s) + \boldsymbol{H_m \Sigma_m}(s) + \boldsymbol{H_{um} \Sigma_{um}}(s) + \boldsymbol{H_{AD} U_{AD}}(s) \tag{9}$$

where

$$\begin{aligned}
\boldsymbol{H_o} &= \boldsymbol{C_c}\left\{s\boldsymbol{I_{n_x}} - \left[\boldsymbol{A} - \boldsymbol{B}(\hat{\boldsymbol{C}}_c\hat{\boldsymbol{B}})^+\boldsymbol{C_c}\hat{\boldsymbol{A}} + \boldsymbol{B}(\hat{\boldsymbol{C}}_c\hat{\boldsymbol{B}})^+\boldsymbol{C_d A_d T}\right]\right\}^{-1} \in \Re^{n_{yc}\times n_x} \\
\boldsymbol{H_R} &= \boldsymbol{H_o B}(\hat{\boldsymbol{C}}_c\hat{\boldsymbol{B}})^+\left(\boldsymbol{C_d B_d} + \boldsymbol{D_d} s\boldsymbol{I_{n_{yc}}}\right) \\
\boldsymbol{H_m} &= \boldsymbol{H_o B} \\
\boldsymbol{H_{um}} &= \boldsymbol{H_o B_{um}} \\
\boldsymbol{H_{AD}} &= \boldsymbol{H_o B}(\hat{\boldsymbol{C}}_c\hat{\boldsymbol{B}})^+
\end{aligned} \tag{10}$$

with $\boldsymbol{x(0^-)}$ state initial conditions and the previously defined transformation $\boldsymbol{T}$ in eq.7 mapping controller to plant states.

Fully Closed Loop Transfer Matrix with Adaption On

Adding the following net zero terms $\mathbf{0} = H_o B(\hat{C}_c\hat{B})^+ C_1(\hat{C}_c\hat{B})\Sigma_m - H_o B(\hat{C}_c\hat{B})^+ C_1(\hat{C}_c\hat{B})\Sigma_m + H_o B_{um}(\hat{C}_c\hat{B})^+ C_2(\hat{C}_c\hat{B})\Sigma_{um} - H_o B_{um}(\hat{C}_c\hat{B})^+ C_2(\hat{C}_c\hat{B})\Sigma_{um}$ yields the washout filter analogy for the design of the low-pass filters

$$
\begin{aligned}
Y_c = {} & H_o x(0^-) + H_o B(\hat{C}_c\hat{B})^+ (C_d B_d + D_d s I_{y_c})\, R \\
& + \left(H_o B \left[I_{n_u} - (\hat{C}_c\hat{B})^+ C_1(\hat{C}_c\hat{B})\right]\right)\Sigma_m + \left[H_o B(\hat{C}_c\hat{B})^+ C_1(\hat{C}_c\hat{B})\right](\Sigma_m - \hat{\Sigma}_m) \\
& + \left(H_o B_{um}\left[I_{n_u} - (\hat{C}_c\hat{B})^+ C_2(\hat{C}_c\hat{B})\right]\right)\Sigma_{um} \\
& + H_o B_{um}(\hat{C}_c\hat{B})^+ C_2(\hat{C}_c\hat{B})\Sigma_{um} - H_o B(\hat{C}_c\hat{B})^+ C_2(\hat{C}_c\hat{B})\hat{H}_m^{-1}\hat{H}_{um}\hat{\Sigma}_{um}
\end{aligned}
\tag{12}
$$

Design Optimization for Adaptive Elements

Therefore, we consider the following design problem, described as optimization of adaptive performance while retaining a desired set of minimum stability margins [Hovakimyan 2010].

$$\begin{aligned}
&\min_{C_1(s)} \left\| H_m \left[I_{n_u} - (\hat{C}_c \hat{B})^+ C_1 (\hat{C}_c \hat{B}) \right] \right\|_{\mathcal{L}_1} \\
&\min_{C_2(s)} \left\| \left(H_{um} \left[I_{n_u} - (\hat{C}_c \hat{B})^+ C_2 (\hat{C}_c \hat{B}) \right] \right) \right\|_{\mathcal{L}_1} \\
&\quad s.t.\ C_1(0) = C_2(0) = I_{n_{yc}} \text{ and } \left\| L_{o,i} \right\| > 6 \text{ dB and } \angle L_{o,i} > 45 \text{ deg} \\
&\quad \text{and } \{\lambda_{m1}, \lambda_{um1}, \lambda_{um2}\} < 1.0
\end{aligned} \tag{15}$$

where $L_{o,i}$ denotes two open loop transfer function matrices to be considered as a constraint, with L_o the open loop return broken at the plant output (control variable feedback) and L_i the open loop return broken at the plant input (effector).

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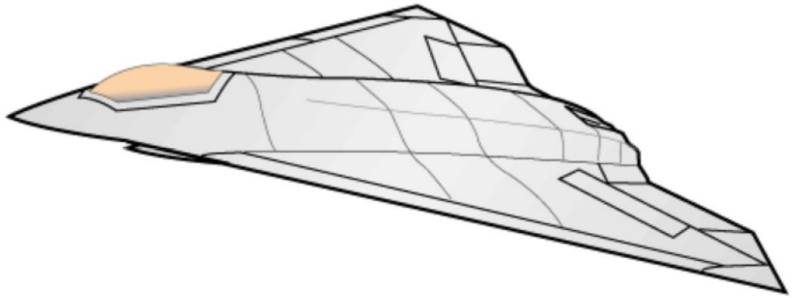
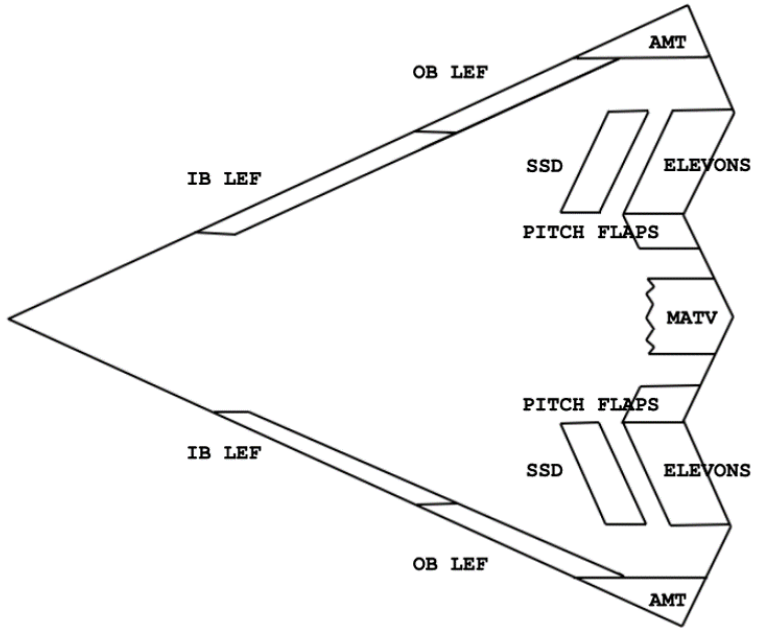
INNOVATIVE CONTROL EFFECTORS AIRCRAFT

- Conceptual tailless fighter designed under AFRL Innovative Control Effectors program
- 14 total control effectors
- Highly nonlinear, unstable dynamics
- 6-DOF nonlinear simulation implemented in MATLAB/Simulink®
  - High-fidelity CFD/wind tunnel aerodynamic database (Niestroy et al. AIAA-2017-1757)
  - Low-fidelity vortex lattice aerodynamic database
  - Static propulsion model with representative lag
  - Second order actuator models with aerodynamic hinge moments
- Baseline nonlinear dynamic inversion control law using low-fidelity on-board model
  - Roll rate, pitch rate, angle-of-sideslip command system





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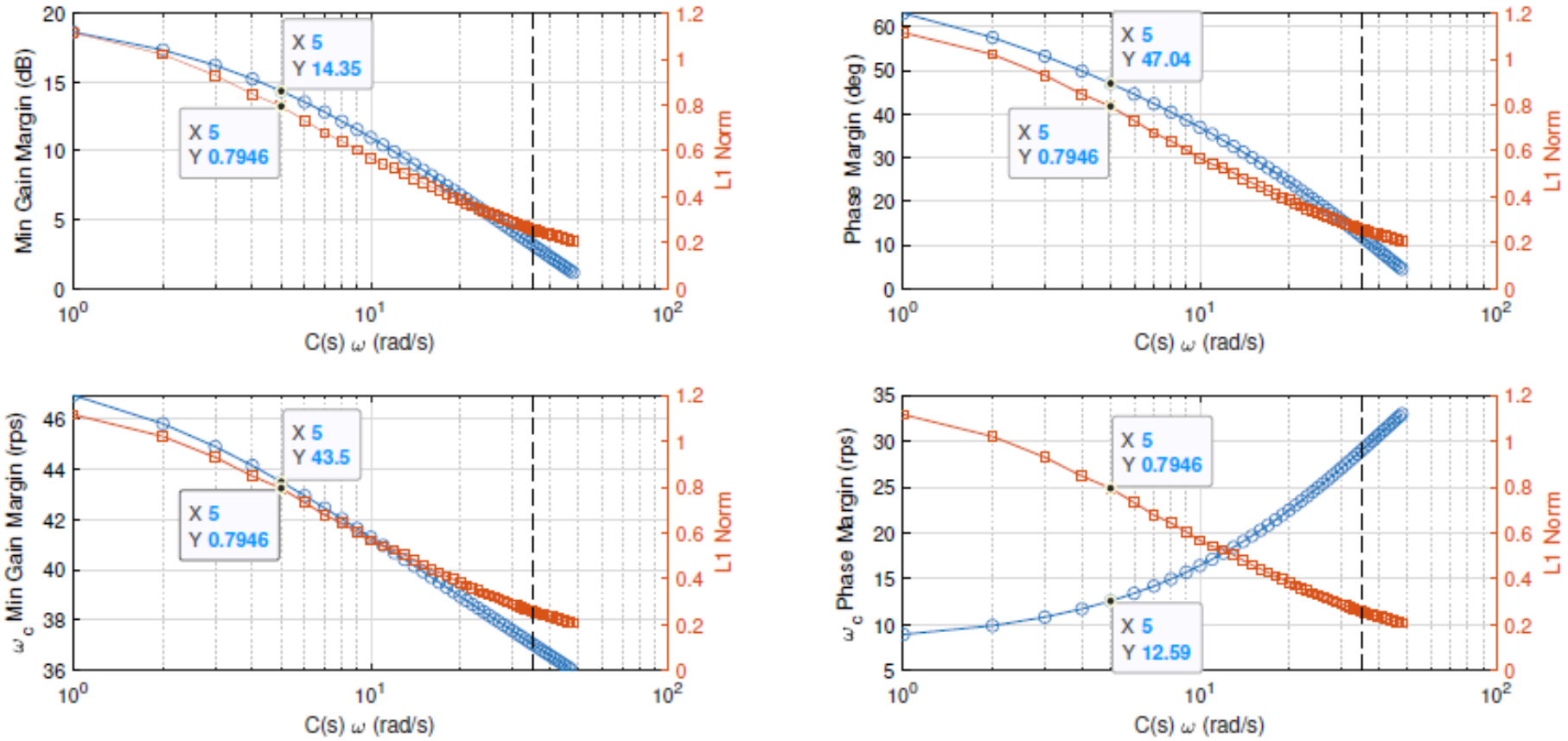

Figure: $\mathcal{L}_1$ Matched Low Pass Filter Design Point Search for $C_1 = \frac{\omega}{s+\omega}$ with $C_2 = \frac{\omega_u}{s+\omega_u} = \frac{20}{s+20}$

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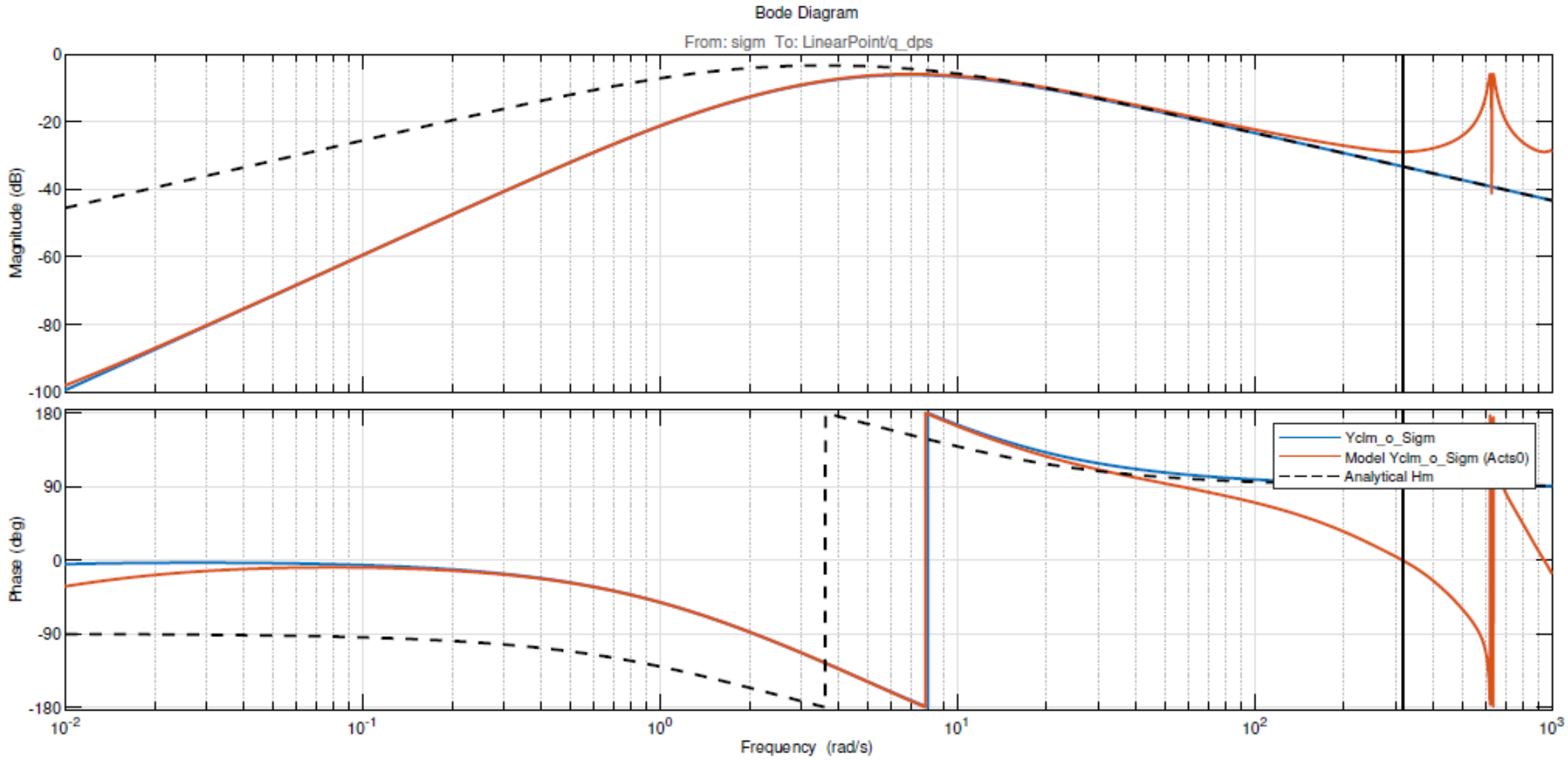

Figure: $\frac{Y_{clm}}{\Sigma_m} = \frac{180}{\pi} M_{\delta_e} \frac{s^2}{(s+\omega)(s^2+2\zeta_{sp}\omega_{sp}+\omega_{sp}^2)} = \frac{-6.8284s^2}{(s+5)(s+8.567)(s+1.513)}, C_1 = \frac{5}{s+5}$

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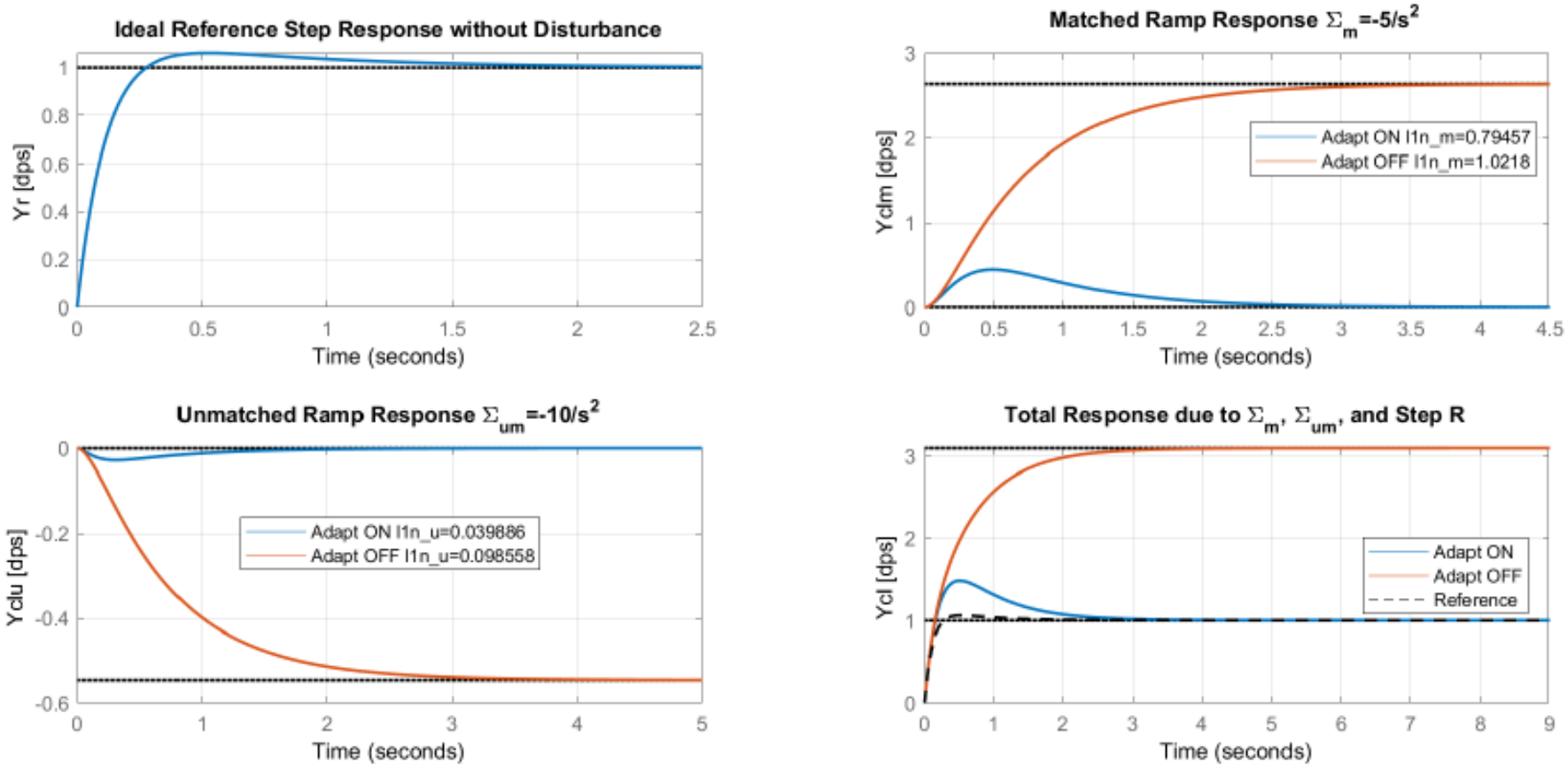

Figure: Summary with Type II Ramp Disturbances on Analytic System

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USAFA Cadets & Staff and Lockheed Martin Engineers observing Stryker.

Stryker coming in for a landing.

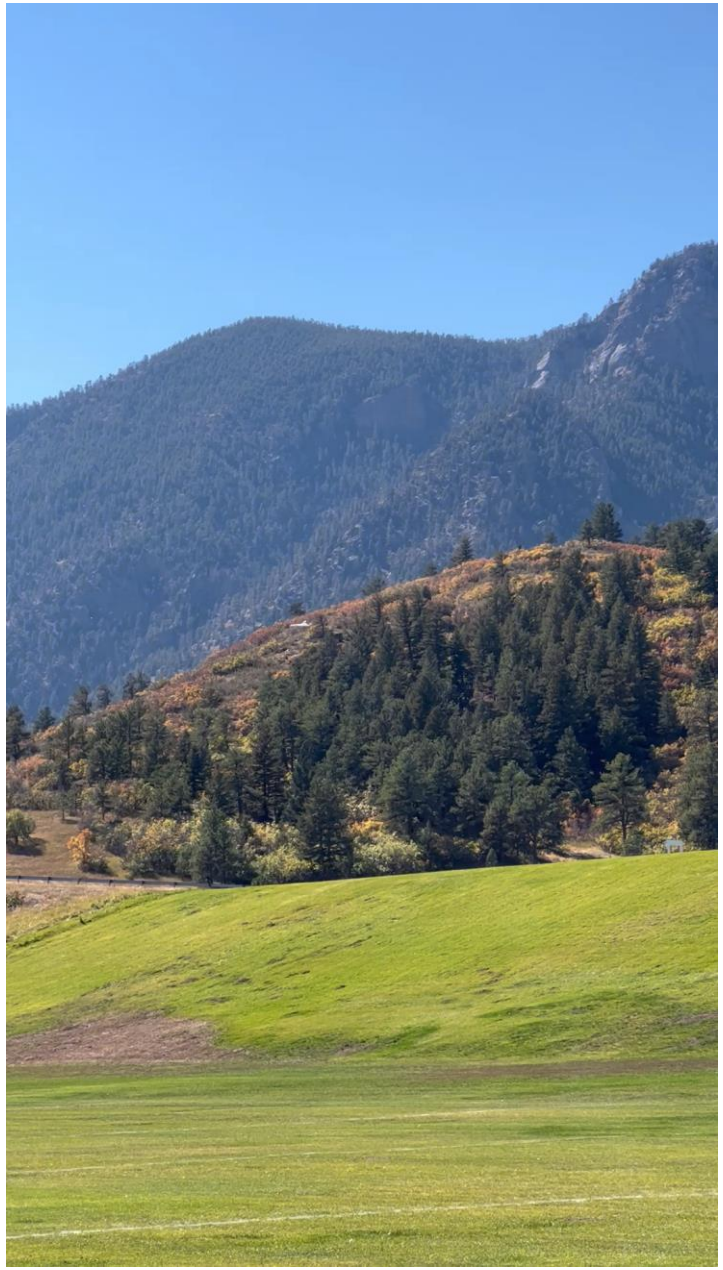
LMAero ONR USAFA

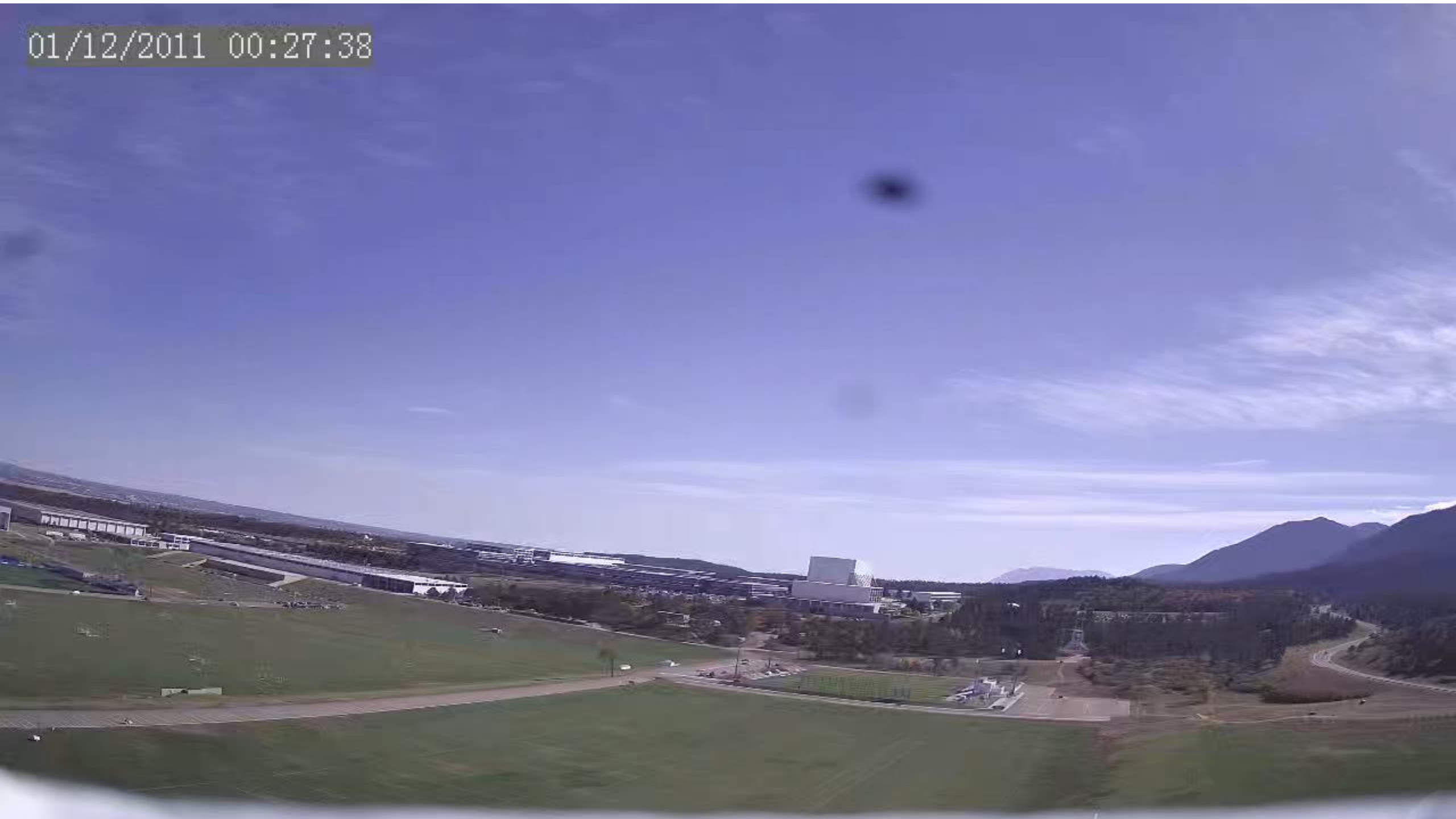
Office of Naval Research ONR Science & Technology

ACCOMMODARE DISCE MEMENTO

SAFE PHASE I

LOCKHEED MARTIN

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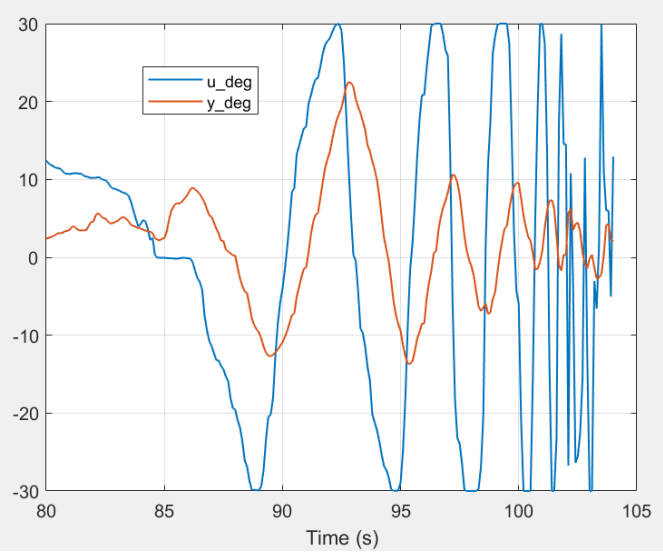

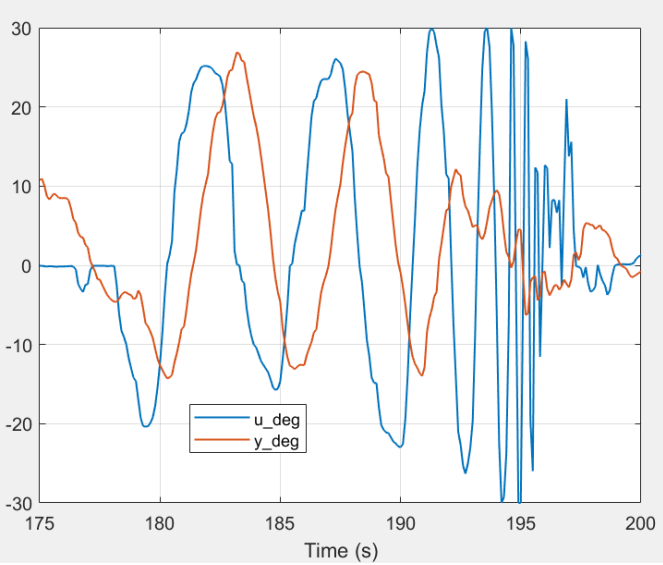

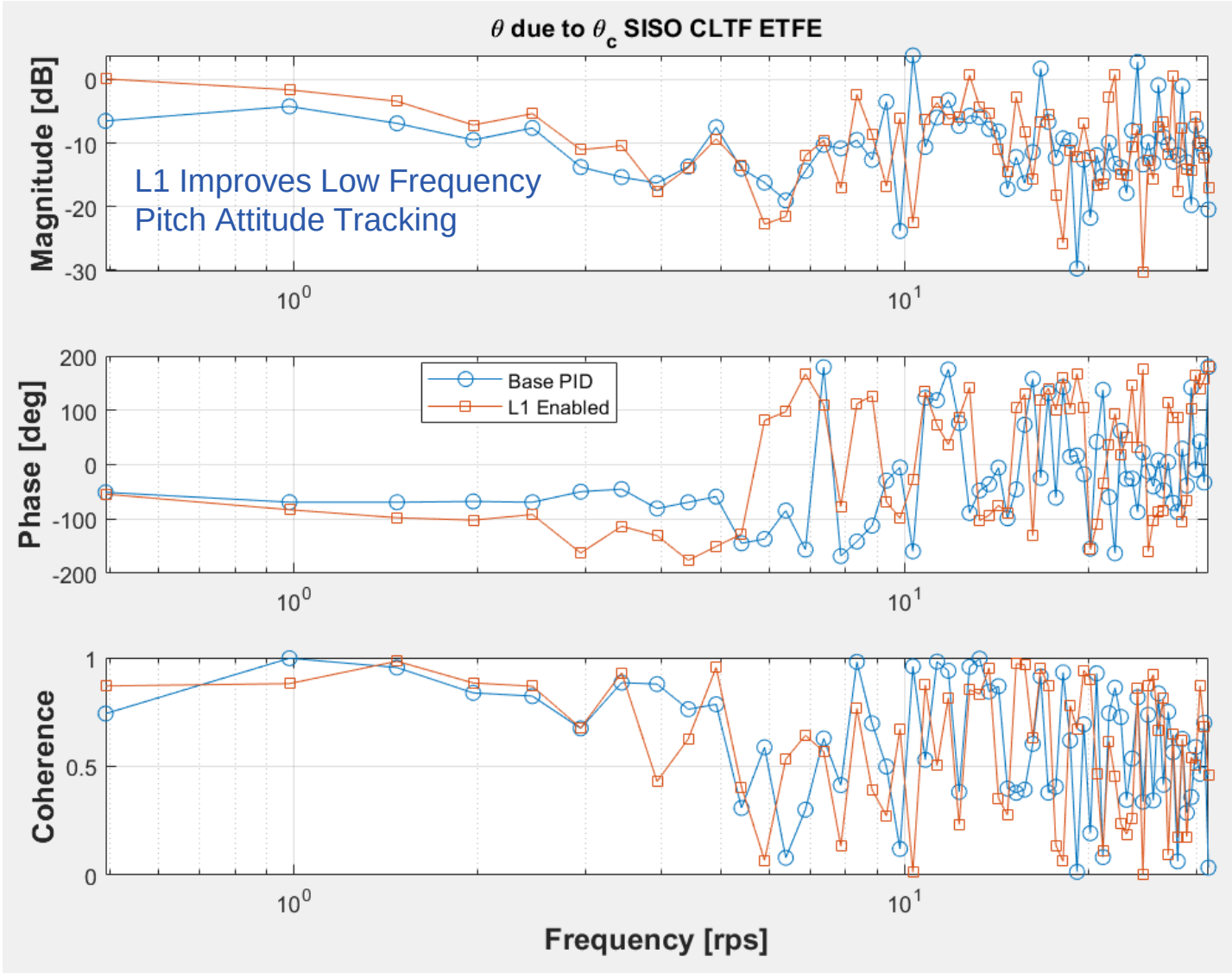

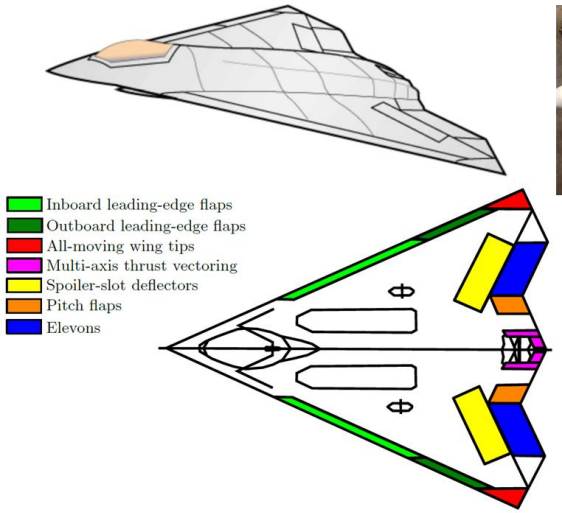

ICE 101-3 Tailless Fighter

USAFA S-200 & ICE UAS

USAF TPS X-62 (NF-16D VISTA)

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Thank You
Questions, please email
Chris Elliott, christopher.m.elliott@lmco.com