Lecture – 38

Robust Nonlinear Control of Aircrafts Using Neuro-adaptive Augmented Dynamic Inversion

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References

Radhakant Padhi, Narayan P. Rao, Siddharth Goyal and Abha Tripathi, "*A Model-Following Neuro-Adaptive Approach for Robust Control of High Performance Aircrafts*", Automatic Control in Aerospace, Vol. 3, No. 1, May 2010.

Problem Statement

- **Pilot Commands:**
  - Case -1: Longitudinal
    (Roll Rate = 0, **Normal Acceleration**, Lateral Acceleration = 0, Total Velocity)
  - Case -2: Lateral
    (**Roll Rate**, **Height**, Lateral Acceleration = 0, Total Velocity)
- **Turn Coordination:** *Lateral acceleration command is **zero***
- **Goal:**
  - Airplane responds to the pilot commands "quickly" & "nicely"
  - The control design should have sufficient robustness for parametric inaccuracies (mass, MI and aerodynamic coefficients)

Note: Essentially it is a **Robust Tracking** problem

Airplane Dynamics: Six Degree-of-Freedom Model

Ref: Roskam J., Airplane Flight Dynamics and Automatic Controls, *1995*

$$\dot{U} = VR - WQ - g\sin\Theta + \frac{1}{m}\left(F_{A_X} + F_{T_X}\right)$$

$$\dot{V} = WP - UR + g\sin\Phi\cos\Theta + \frac{1}{m}\left(F_{A_Y} + F_{T_Y}\right)$$

$$\dot{W} = UQ - VP + g\cos\Phi\cos\Theta + \frac{1}{m}\left(F_{A_Z} + F_{T_Z}\right)$$

$$\dot{P} = c_1 QR + c_2 PQ + c_3\left(L_A + L_T\right) + c_4\left(N_A + N_T\right)$$

$$\dot{Q} = c_5 PR - c_6\left(P^2 - R^2\right) + c_7\left(M_A + M_T\right)$$

$$\dot{R} = c_8 PQ - c_2 QR + c_4\left(L_A + L_T\right) + c_9\left(N_A + N_T\right)$$

$$\dot{\Phi} = P + Q\sin\Phi\tan\Theta + R\cos\Phi\tan\Theta$$

$$\dot{\Theta} = Q\cos\Phi - R\sin\Phi$$

$$\dot{\Psi} = \left(Q\sin\Phi + R\cos\Phi\right)\sec\Theta$$

$$\begin{bmatrix}\dot{x}_E\\ \dot{y}_E\\ \dot{z}_E\end{bmatrix} = \begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\theta & 0 & \sin\theta\\ 0 & 1 & 0\\ -\sin\theta & 0 & \cos\theta\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi & \cos\phi\end{bmatrix}\begin{bmatrix}U\\ V\\ W\end{bmatrix}$$

$$\dot{h} = U\sin\Theta - V\cos\Theta\sin\Phi - W\cos\Theta\cos\Phi$$

Aerodynamic Model (F-16)

Ref: Eugene A. Morelli , American Control Conference Philadelphia, Pennsylvania June 1998

$$C_{x_t} = C_x(\alpha, \delta_e) + C_{x_q}(\alpha)\tilde{q}$$

$$C_{y_t} = C_y(\beta, \delta_a, \delta_r) + C_{y_p}(\alpha)\tilde{p} + C_{y_r}(\alpha)\tilde{r}$$

$$C_{z_t} = C_z(\alpha, \beta, \delta_e) + C_{z_q}(\alpha)\tilde{q}$$

$$C_{l_t} = C_l(\alpha, \beta) + C_{l_p}(\alpha)\tilde{p} + C_{l_r}(\alpha)\tilde{r} + C_{l\delta_a}(\alpha, \beta)\delta_a + C_{l\delta_r}(\alpha, \beta)\delta_r$$

$$C_{m_t} = C_m(\alpha, \delta_e) + C_{m_q}(\alpha)\tilde{q} + C_z(x_{cg_{ref}} - x_{cg})$$

$$C_{n_t} = C_n(\alpha, \beta) + C_{n_p}(\alpha)\tilde{p} + C_{n_r}(\alpha)\tilde{r} + C_{n\delta_a}(\alpha, \beta)\delta_a + C_{n\delta_r}(\alpha, \beta)\delta_r + C_y(x_{cg_{ref}} - x_{cg})\left(\frac{\bar{c}}{b}\right)$$

$$\tilde{p} = pb / 2V_T \quad \tilde{q} = q\bar{c} / 2V_T \quad \tilde{r} = rb / 2V_T$$

Equations in Desired Form

$$\dot{X}_V = f_V(X) + [g_V(X)]\, U_c$$

$$\dot{X}_R = f_R(X) + [g_R(X)]\, U_c$$

where

$$X \triangleq [V_T \quad \alpha \quad \beta \quad P \quad Q \quad R \quad \Phi \quad \Theta \quad \Psi \quad X_E \quad Y_E \quad h]^T$$

$$X_V \triangleq [U \quad V \quad W]^T$$

$$X_R \triangleq [P \quad Q \quad R]^T$$

$$X_A \triangleq [\Phi \quad \Theta \quad \Psi]^T$$

$$U_c \triangleq [U_{AER} \quad U_T]^T \triangleq [[\delta_a \quad \delta_e \quad \delta_r] \quad T]^T$$

Definitions and Goal

- Total Velocity: V_T
- Roll Rate (about x-axis): P
- Normal Acceleration: $n_z \triangleq -(F_z/m) = -(1/m)\left(F_{A_z}\right)$
- Lateral Acceleration: $n_y \triangleq \ (F_y/m) = \ (1/m)\left(F_{A_y}\right)$
- Goal: $P \to P^*, \quad n_z \to n_z^*, \quad n_y \to n_y^* = 0, \quad V_T \to V_T^*$

where P^*, n_z^*, V_T^* are pilot commands

Control Synthesis Procedure

- Define new variables: $a_z \triangleq n_z + \dot{W}, \quad a_z^* \triangleq n_z^* + \dot{W}$
  $a_y \triangleq n_y - \dot{V}, \quad a_y^* \triangleq n_y^* - \dot{V}$
- Key observation: $\ddot{V} = \ddot{W} = 0$

$$\left(\begin{bmatrix} n_z & n_y \end{bmatrix}^T \rightarrow \begin{bmatrix} n_z^* & n_y^* \end{bmatrix}^T \right) \Leftrightarrow \left(\begin{bmatrix} a_z & a_y \end{bmatrix}^T \rightarrow \begin{bmatrix} a_z^* & a_y^* \end{bmatrix}^T \right)$$

- Known:

$$n_z = f_{n_z} + g_{n_z} U_c \qquad \dot{P} = f_P + g_P U_c$$

$$n_y = f_{n_y} + g_{n_y} U_c \qquad \dot{V}_T = f_{V_T} + g_{V_T} U_c$$

- In Wind Axis Frame: $n_{wz} = f_{n_{wz}} + g_{n_{wz}} U_c$

Control Synthesis Procedure: Longitudinal

- Dynamics:

$$a_z = UQ - VP + g\cos\Phi\cos\Theta$$

$$a_y = UR - WP - g\sin\Phi\cos\Theta$$

- Differentiate:

$$\dot{a}_z = f_{a_z} + g_{a_z} U_c$$

$$\dot{a}_y = f_{a_y} + g_{a_y} U_c$$

- **Case-1: (Longitudinal)** Pilot commands:
  - Roll Rate: $P^* = 0$
  - Normal Acceleration: n_z^*
  - Lateral Acceleration: $n_y^* = 0$
  - Total Velocity: V_T*

Control Synthesis Procedure: Longitudinal

- **Define (Errors):**

Fast Variables $\hat{X}_T \triangleq \begin{bmatrix} \hat{P} & \hat{a}_z & \hat{a}_y \end{bmatrix}^T \triangleq \begin{bmatrix} \left(P - P^*\right) & \left(a_z - a_z^*\right) & \left(a_y - a_y^*\right) \end{bmatrix}^T$

Slow Variables $\hat{V}_T \triangleq \left[(V_T - V_T^*) \right]$

- Design a controller such that:

$$\dot{\hat{X}}_T + K\,\hat{X}_T = 0,$$

$$\dot{\hat{V}}_T + K_{V_T}\,\hat{V}_T = 0,$$

$$K \triangleq diag\left(\frac{1}{\tau_P}, \ \frac{1}{\tau_{n_z}}, \ \frac{1}{\tau_{n_y}}\right) \qquad K_{V_T} \triangleq diag\left(\frac{1}{\tau_{V_T}}\right)$$

Control Synthesis Procedure: Longitudinal

- **Calculate** $\left[U_{AER}\right]$ **for every** Δt **time**

$$U_{AER} = \left[A_U\right]^{-1} b_U$$

$$A_U \triangleq \begin{bmatrix} g_P \\ g_{a_z} \\ g_{a_y} \end{bmatrix} + \left[K\right]\begin{bmatrix} 0 & g_{n_z} & g_{n_y} \end{bmatrix}^T, \qquad b_U \triangleq \left[K\right]\begin{bmatrix} P - P^* \\ n_z - n_z^* \\ n_y - n_y^* \end{bmatrix} - \begin{bmatrix} f_P \\ f_{a_z} \\ f_{a_y} \end{bmatrix}$$

- **Calculate** U_T **for every** $5 \cdot \Delta t$ **time**

$$U_T = -\left[d_{V_T}\right]^{-1} c_{V_T}$$

$$c_{V_T} = \left[\left(f_{V_T} + g_{V_T} U_{AER}\right) - \dot{V}_T^* + K_{V_T}\left(V_T - V_T^*\right)\right]$$

Control Synthesis Procedure: Lateral

- **Case-2: (Lateral)** Pilot commands:
  - Roll Rate: P^*
  - Height: h^*
  - Lateral Acceleration: $n_y^* = 0$
  - Total Velocity: V_T^*

- Generation of Θ^* command:
  - Define $\hat{h} \triangleq \left(h - h^*\right)$ and aim for $\dot{\hat{h}} + \left(1/\tau_h\right)\hat{h} = 0$

$$\left[U\sin\Theta - V\cos\Theta\sin\Phi - W\cos\Theta\cos\Phi\right] - \dot{h}^* + \left(1/\tau_h\right)\left(h - h^*\right) = 0$$

  - Solve for $\Theta \triangleq \Theta^*$

Control Synthesis Procedure: Lateral

- Generation of Q^* command:
  - Define $\hat{\Theta} = (\Theta - \Theta^*)$ and aim for $\dot{\hat{\Theta}} + (1/\tau_\Theta)\hat{\Theta} = 0$

$$(Q\cos\Phi - R\sin\Phi) - \dot{\Theta}^* + (1/\tau_\Theta)(\Theta - \Theta^*) = 0$$

  - Solve for $Q \triangleq Q^*$

- Control Computation:
  - Define (Errors):

Fast Variables $\hat{X}_T \triangleq \begin{bmatrix} \hat{P} & \hat{Q} & \hat{a}_y \end{bmatrix}^T \triangleq \begin{bmatrix} (P - P^*) & (Q - Q^*) & (a_y - a_y^*) \end{bmatrix}^T$

Slow Variable $\hat{V}_T \triangleq \left[(V_T - V_T^*) \right]$

Control Synthesis Procedure: Lateral

- Design a controller such that

$$\dot{\hat{X}}_T + K\hat{X}_T = 0 \qquad \dot{\hat{V}}_T + K_{V_T}\hat{V}_T = 0$$

$$K \triangleq diag\left(\frac{1}{\tau_P}, \frac{1}{\tau_Q}, \frac{1}{\tau_{n_y}}\right) \qquad K_{V_T} \triangleq diag\left(\frac{1}{\tau_{V_T}}\right)$$

- After some algebra, Finally:

$$U_c = \left[[A_U^{-1}\, b_U]^T \quad T\right]^T$$

$$A_U \triangleq \left[g_P^T \quad g_Q^T \quad \left(g_{a_y}^T + (1/\tau_{n_y})g_{n_y}^T\right)\right]^T$$

$$b_U \triangleq -\left[f_P \quad f_Q \quad f_{a_y}\right]^T - K\left[\left(P - P^*\right) \quad \left(Q - Q^*\right) \quad \left(f_{n_y} - n_y^*\right)\right]^T$$

Control Synthesis Procedure:
Combined Longitudinal & Lateral

- **Case-3: (Combined Longitudinal and Lateral)**

  Pilot commands:

  - Roll Rate (about velocity vector): P_w^*
  - Normal Acceleration: n_z^*
  - Lateral Acceleration: $n_y^* = 0$
  - Total Velocity: V_T^*

- Generation of P^* command:
  - Define P^* in the desired form as: $P^* = f_{P^*} + g_{P^*} U_A$

where $$f_{P^*} = (1/\cos\alpha(\cos\beta + \tan\beta\sin\beta))(P_w^* - R\sin\alpha(\sin\beta\tan\beta + \cos\beta) - \tan\beta(f_{n_{wz}}/V_T) + (g/V_T)\cos\gamma\cos\Phi$$

and $$g_{P^*} = (-\tan\beta/\cos\alpha(\cos\beta + \tan\beta\sin\beta))(g_{n_{wz}}/V_T)$$

Control Synthesis Procedure:
Combined Longitudinal & Lateral

- Design a controller such that

$$\dot{\hat{X}}_T + K\hat{X}_T = 0 \qquad \dot{\hat{V}}_T + K_{V_T}\hat{V}_T = 0,$$

$$K \triangleq diag\left(\frac{1}{\tau_P}, \frac{1}{\tau_{n_z}}, \frac{1}{\tau_{n_y}}\right) \qquad K_{V_T} \triangleq diag\left(\frac{1}{\tau_{V_T}}\right)$$

- After some algebra, Finally:

$$U_c = \left[[A_U^{-1} b_U]^T \quad T \right]^T$$

$$A_U \triangleq \left[g_P^T \quad g_{a_z}^T \quad g_{a_y}^T \right]^T + K\left[-g_{P^*}^T \quad g_{n_z}^T \quad g_{n_y}^T \right]^T$$

$$b_U \triangleq -\left[f_P \quad f_{a_z} \quad f_{a_y} \right]^T - K\left[\left(P - f_{P^*}\right) \quad \left(f_{n_z} - n_z^*\right) \quad \left(f_{n_y} - n_y^*\right) \right]^T$$

Alternative way to compute P* Command

- Goal: $\Phi \to \Phi^*$ (Note: $\Phi^* = 0$ for longitudinal case)
- Define $\tilde{\Phi} \triangleq \left(\Phi - \Phi^*\right)$
- Desired error dynamics:

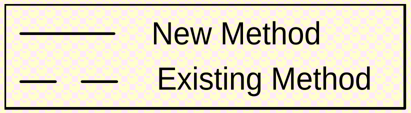
$$\dot{\tilde{\Phi}} + \left(1/\tau_\Phi\right)\tilde{\Phi} = 0, \qquad \tau_\Phi > 0$$

- Substitute for $\dot{\Phi}$ and solve for $P \triangleq P^*$

$$P^* = \dot{\Phi}^* - \left[Q \sin\Phi \, \tan\Theta + R\cos\Phi \, \tan\Theta + \frac{1}{\tau_\Phi}\left(\Phi - \Phi^*\right) \right]$$

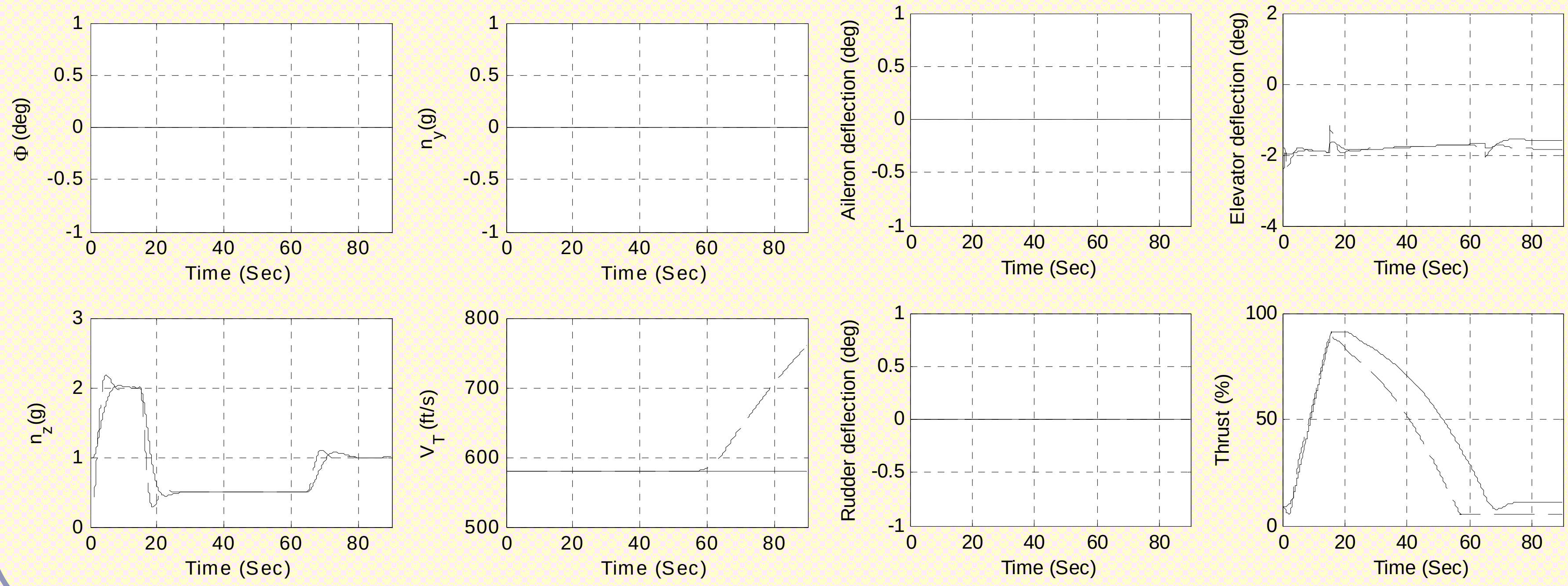
Results: Longitudinal

(With ϕ^* as a command)



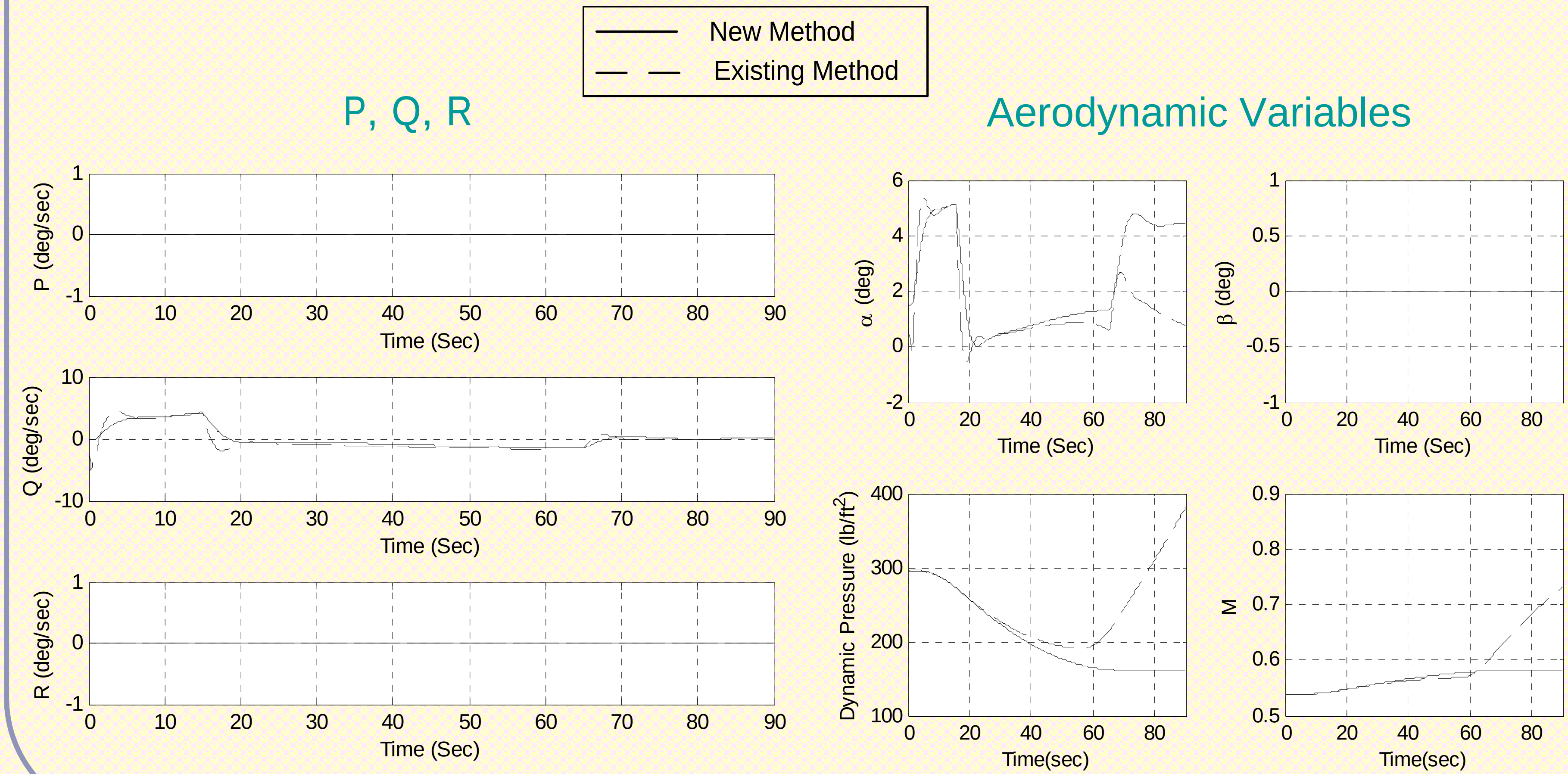
Tracked Variables

Control Variables



Results: Longitudinal

(With ϕ^* as a command)

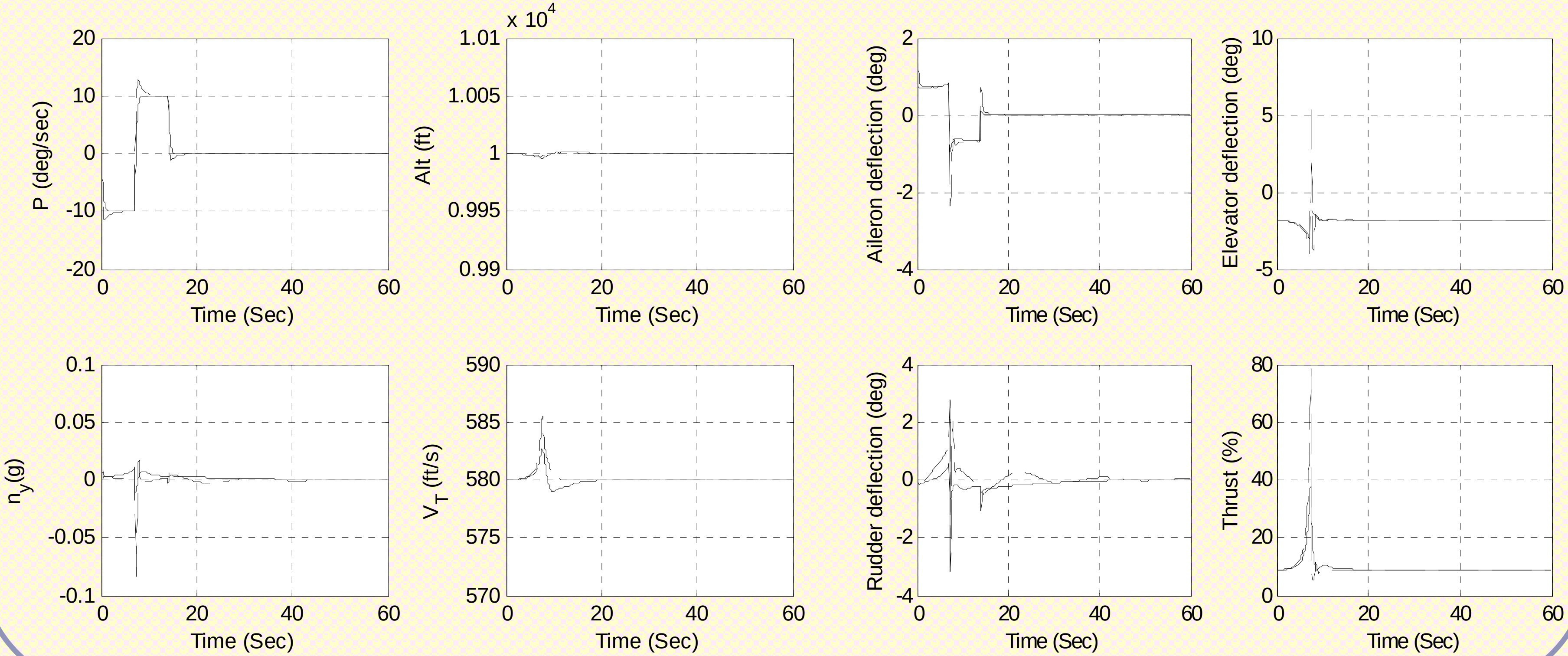


Results: Lateral

(With P* as a command)

Tracked variables | Control variables

New Method — (solid line)
Existing Method — (dashed line)

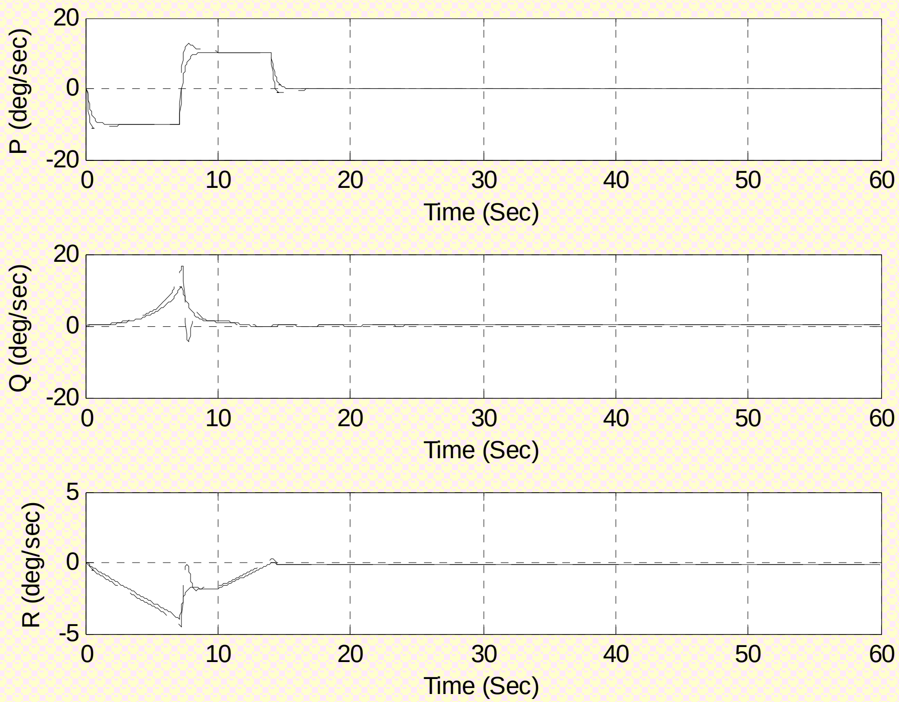


Results: Lateral

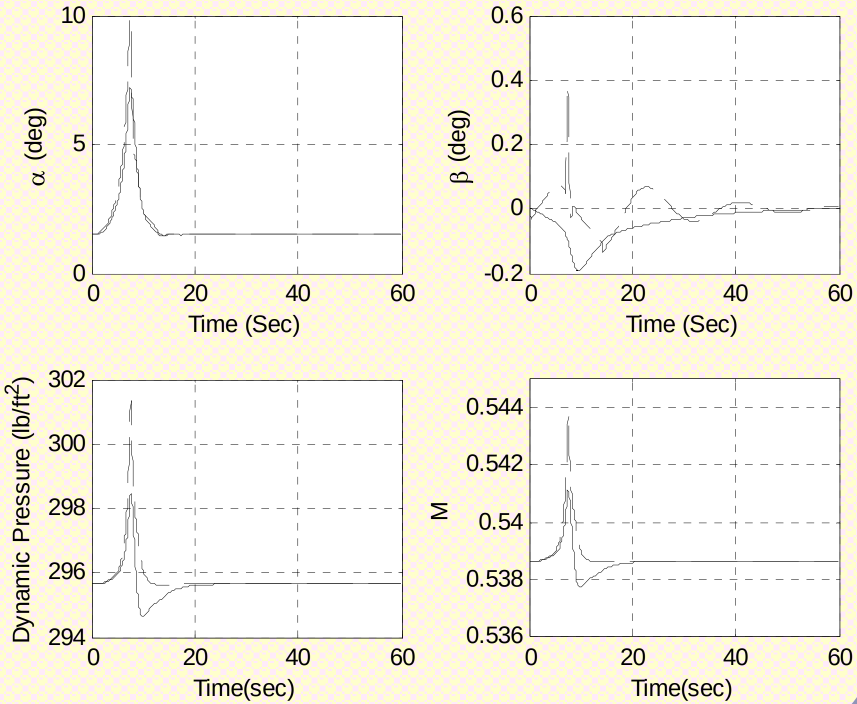
(With P* as a command)

New Method
Existing Method

P, Q, R

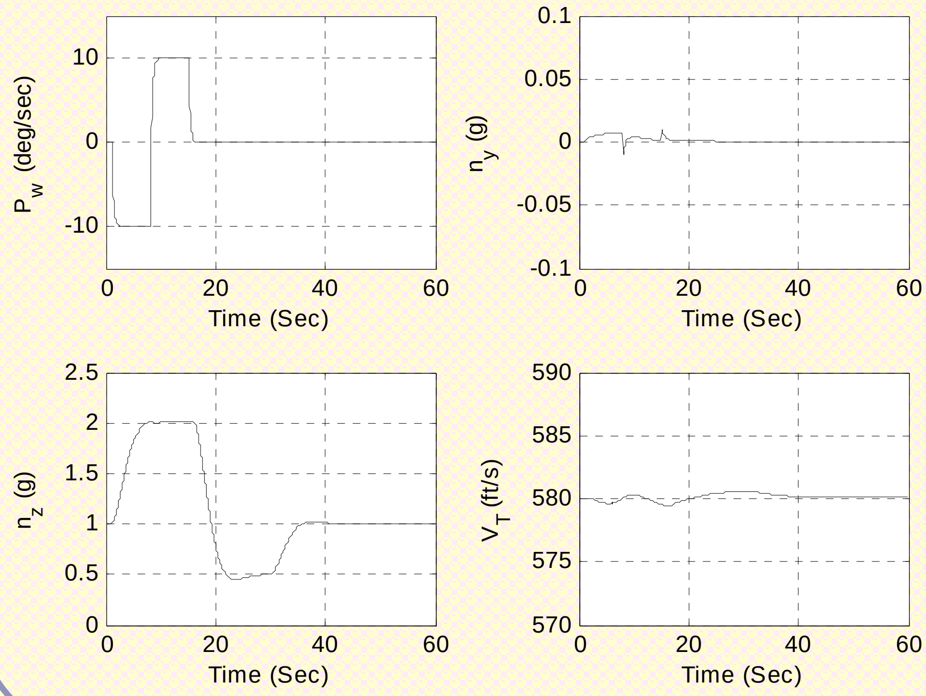


Aerodynamic variables

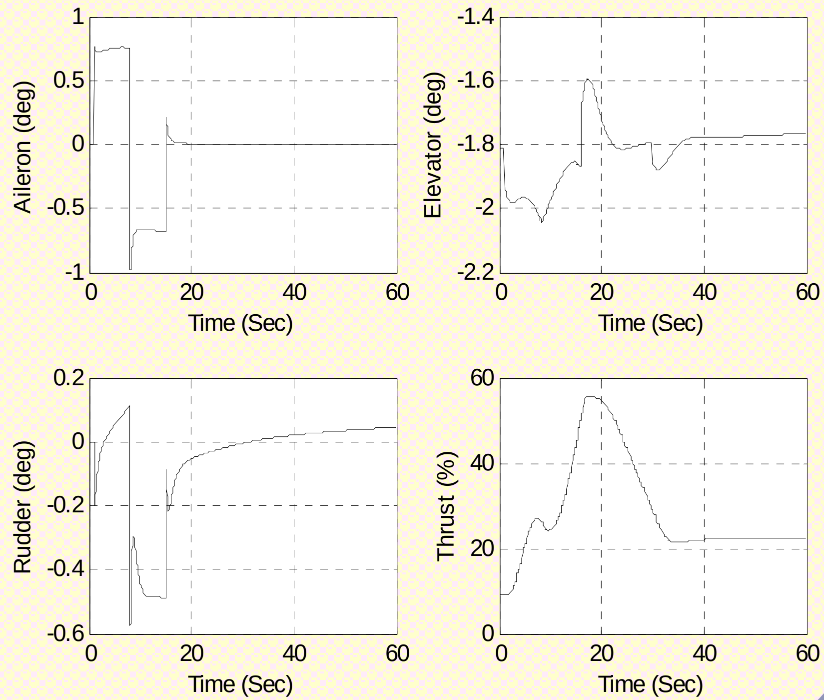


Results: Combined Longitudinal and Lateral

Tracked Variables



Control Variables



Summary: Nominal Controller

Existing Method:

- Assumption: $\dot{V} = \dot{W} = 0$

  $\ddot{\Phi}^* = \ddot{\Theta}^* = \ddot{\Psi}^* = 0$
- More number of design parameters (11 & 12)
- Works

New Method:

- Assumption: $\ddot{V} = \ddot{W} = 0$
- Less number of design parameters (5 & 7)
- Works better...!
  - Lesser control magnitude
  - Smoother transient response
  - Better turn co-ordination

Neuro-Adaptive Control Design for Enhanced Robustness

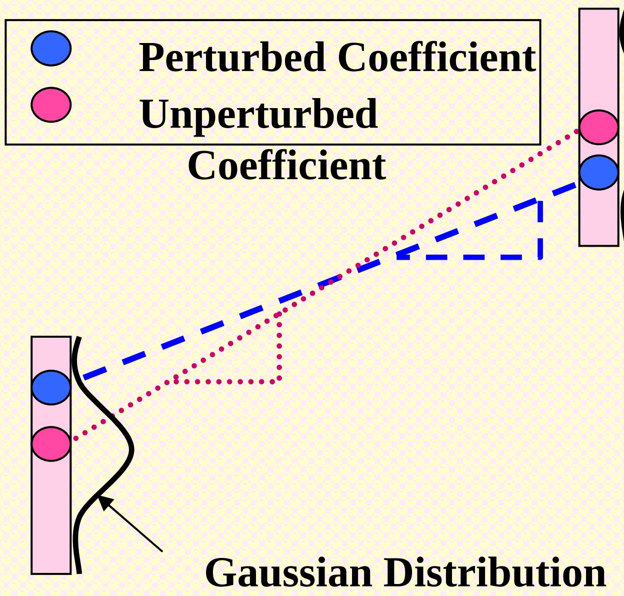
Indian Institute of Science, Bangalore

Objective:

To increase the robustness of the "Nominal Controller" with respect to parameter and/or modeling uncertainties.

Robustness Study

- Parametric uncertainties was introduced in aero-coefficients and inertia parameters using Gaussian distribution around the nominal parameter values
- Since no analytical method for analyzing robustness behavior is available, a stochastic approach has been followed in this paper as an alternative.



Longitudinal Mode

Pilot Commands given:

$V_T^* = V_{T0}; n_z^* = 2g;$

$(\phi^*$ and n_y^* being maintained at zero);

Limits Imposed on the steady state error:

$\phi : \pm 3^\circ; \quad \mathrm{n_y} : \pm 0.05g; \quad V_T = \pm 1\%; \quad n_z = \pm 15\%$

Lateral Mode

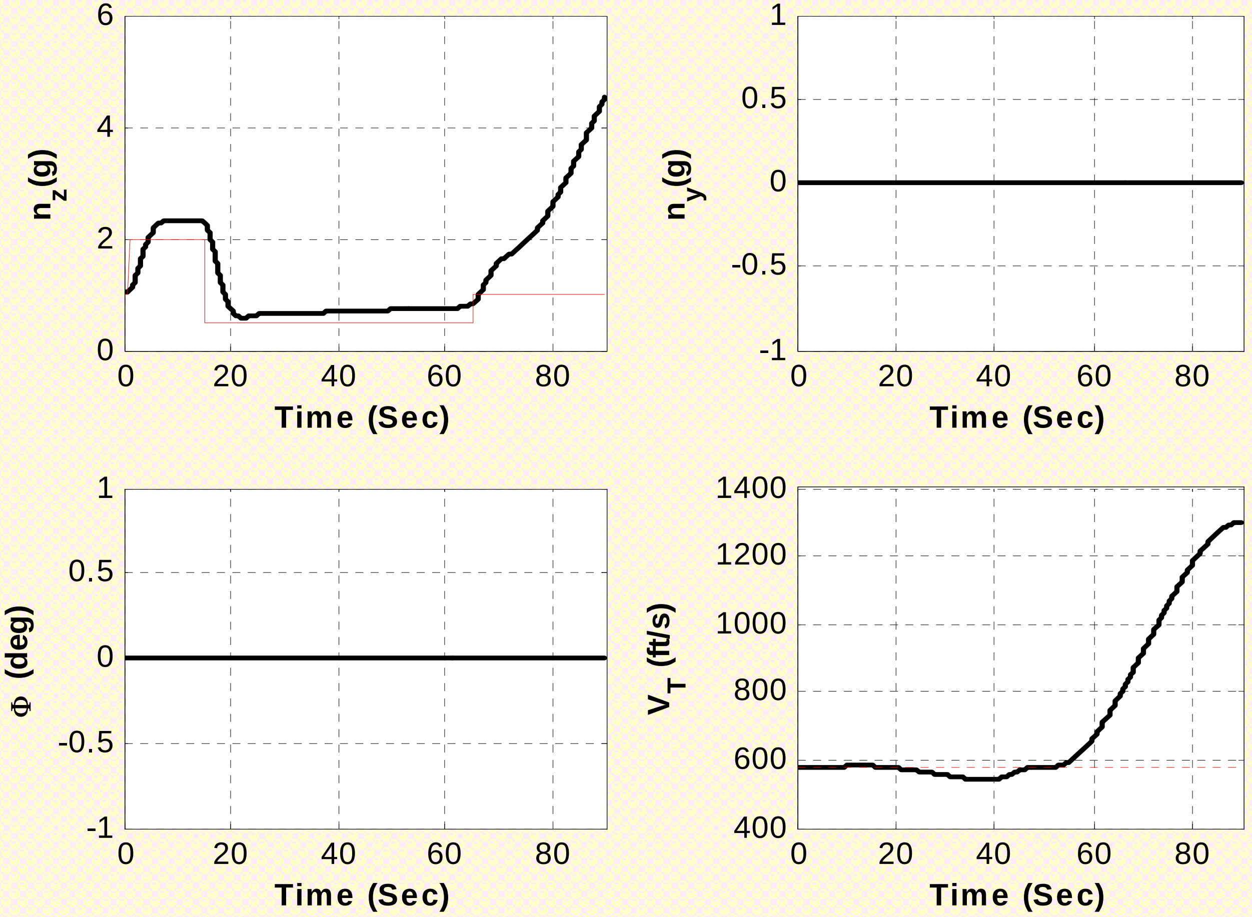
Pilot Commands Given:

$$\phi^* = -40^\circ; \quad V_T^* = V_{T0}; \quad h^* = h_0; \quad n_y^* = 0$$

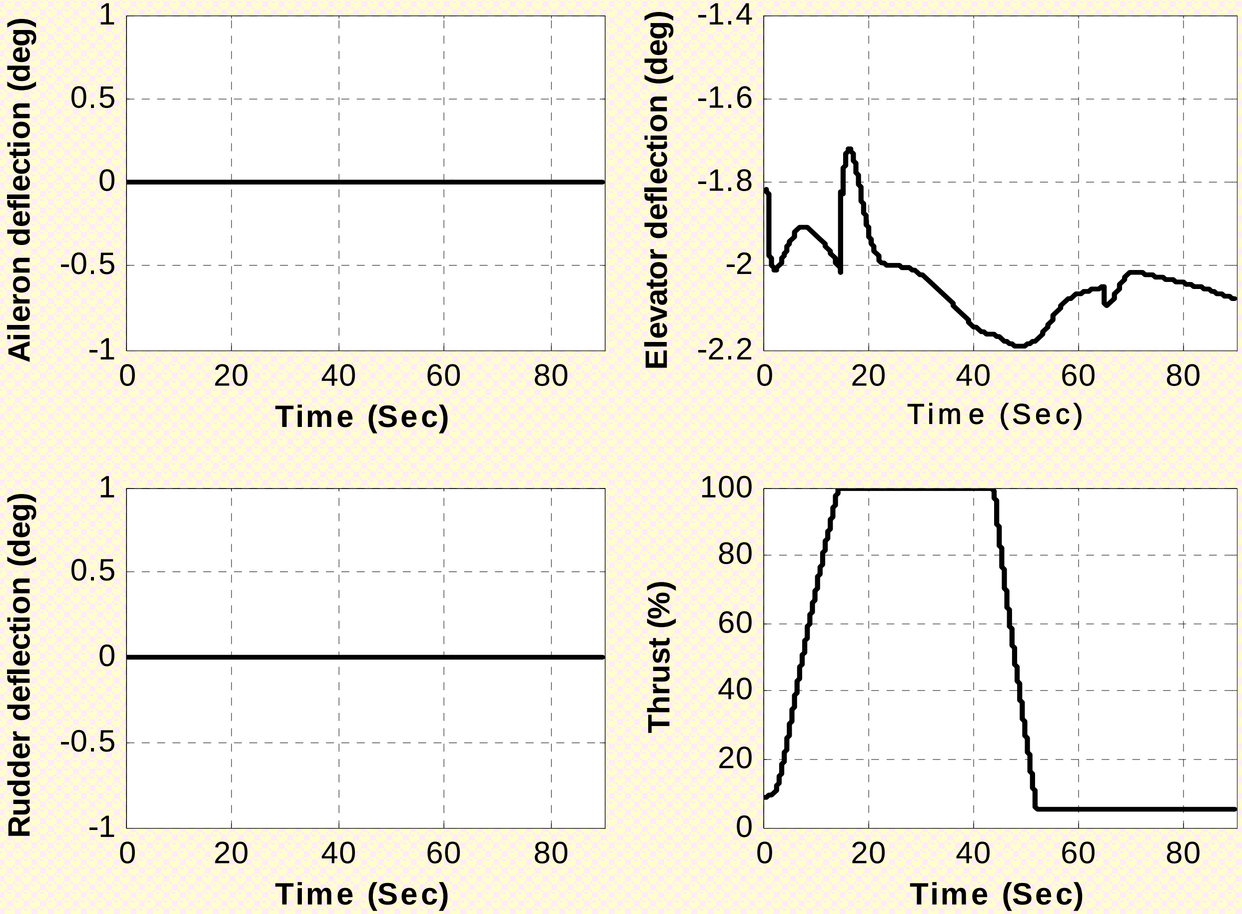
Limits Imposed on the steady state error:

$$\text{h:} \pm 1\%; \quad \text{n}_\text{y} : \pm 0.05g; \quad V_T = \pm 1\%; \quad \phi = \pm 10\%$$

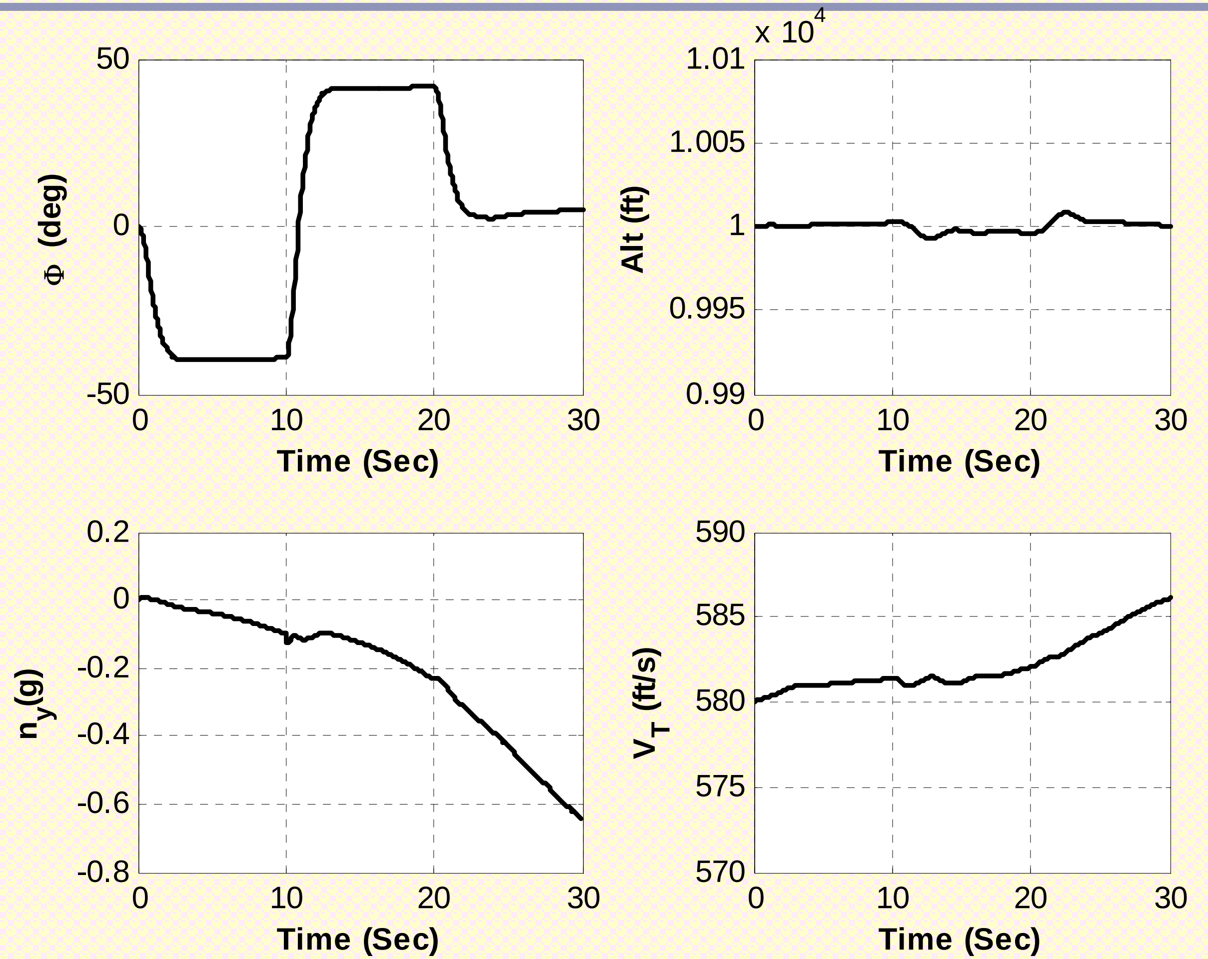
Longitudinal Maneuver (Failure)



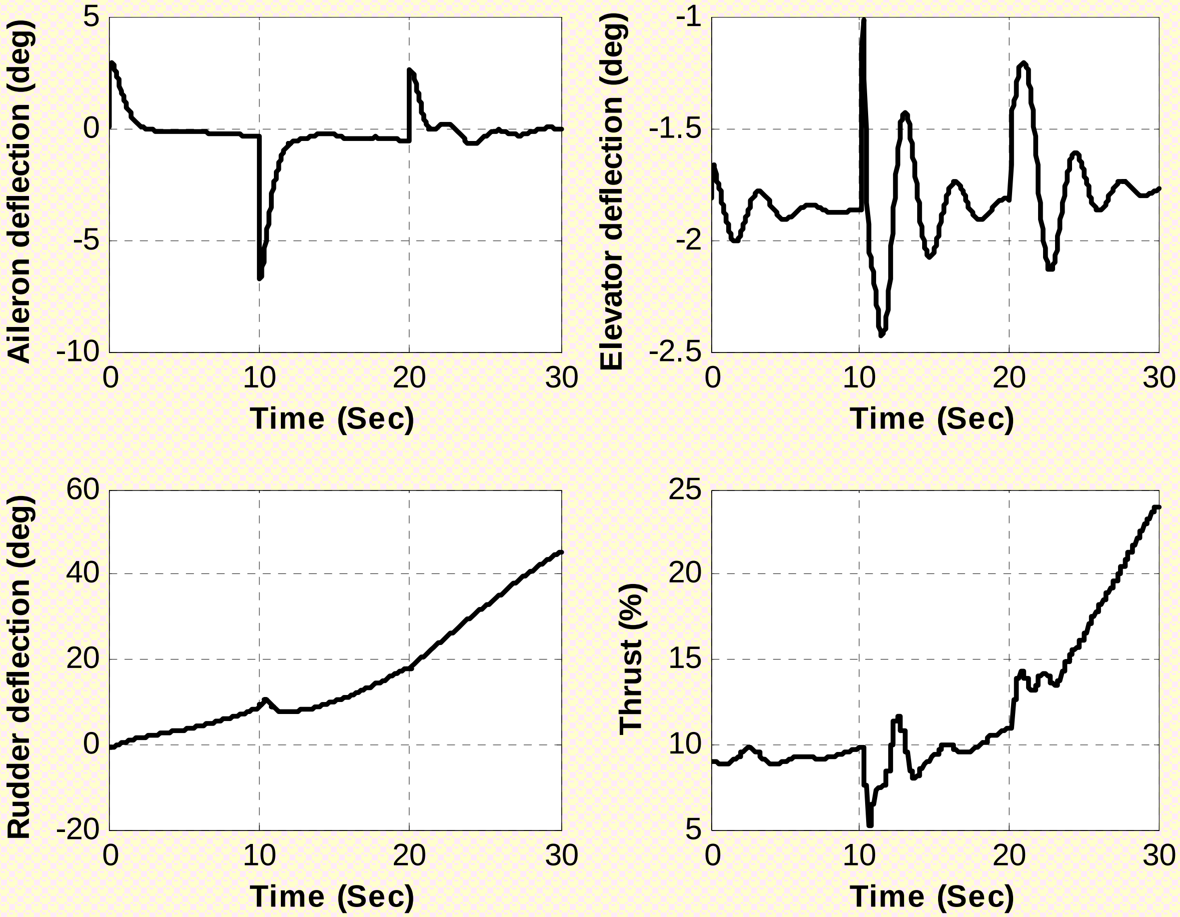
Longitudinal Maneuver (Failure)



Lateral Maneuver (Failure)



Lateral Maneuver (Failure)



Robustness in Longitudinal Mode

Aerodynamic coefficient	*1%*	*1%*	*2%*	*2%*	*5%*	*5%*
Mass and Inertia coefficient	*5%*	*10%*	*5%*	*10%*	*5%*	*10%*
% Success	*100%*	*100%*	*98%*	*96%*	*78%*	*76%*

Robustness in Lateral Mode

Aerodynamic coefficient	*1%*	*1%*	*2%*	*2%*	*5%*	*5%*
Mass and Inertia coefficient	*5%*	*10%*	*5%*	*10%*	*5%*	*10%*
% Success	*100%*	*100%*	*100%*	*100%*	*95%*	*86%*

Neuro-Adaptive Design

- Problem:
  - The DI design sensitive to modeling parameter inaccuracies
- Solution:
  - Enhance Robustness by augmenting the DI with "***Neuro-Adaptive Design***"
- The adaptive design should preferably be compatible with "any" nominal controller

Output Robustness: Robustness of Inner Loop

Desired output dynamics:

$$\dot{Y}_d = f_{Y_d}(X_d) + G_{Y_d}(X_d)U_d$$

Actual output dynamics:

$$\dot{Y} = f_{Y_d}\left(X\right) + G_{Y_d}(X)U + d(X)$$

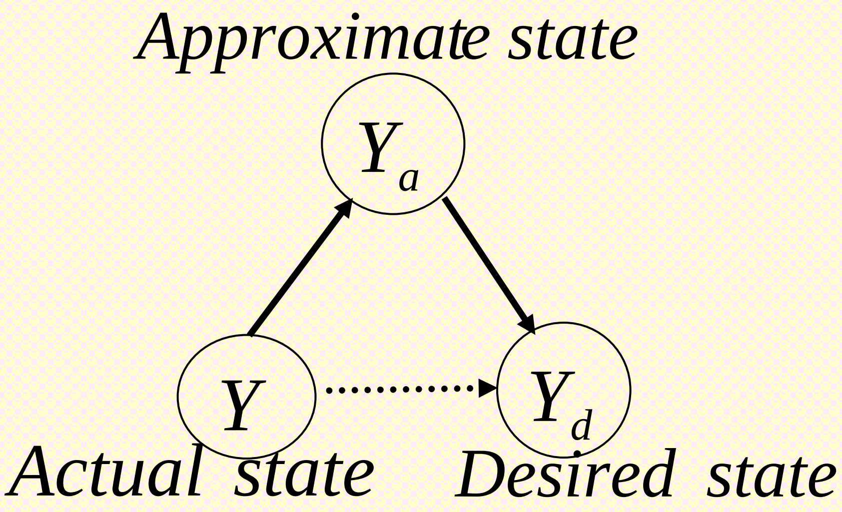
Objective: $Y \rightarrow Y_d$ as soon as possible

N-A for Robustness of Output Dynamics

- Dynamics of auxiliary output:

$$\dot{Y}_a = f_{Y_d}\left(X\right) + G_{Y_d}(X)U + \underbrace{\hat{d}(X)}_{\text{NN Approx.}} + K_a(Y - Y_a)$$

- **Strategy:**



Steps for assuring $Y_a \to Y_d$

- Enforce the error dynamics

$$\dot{E}_d + KE_d = 0 \qquad\qquad E_d \triangleq (Y_a - Y_d)$$

- After carrying out the necessary algebra

$$f(X,U) = h(X, X_a, X_d, U_d)$$

- In case of control affine system

$$f(X) + [g(X)]U = h(X, X_d, X_a, U_d)$$

- The control is given by

$$U = [g(X)]^{-1}\{h(X, X_d, X_a, U_d) - f(X)\}$$

Steps for assuring $Y \rightarrow Y_a$

- The error in the output is defined as

$$E_a \triangleq (Y - Y_a) \qquad e_{a_i} \triangleq (y_i - y_{ai})$$

- Ideal neural network is given by:

$$d_i(X) = W_i^T \varphi_i(X) + \varepsilon_i$$

where W_i is the weight matrix and $\varphi_i(X)$ is the radial basis function

Function Learning:

Define error $e_{a_i} \triangleq (y_i - y_{a_i})$

Output dynamics

$$\dot{y}_i = f_{Y_i}(X) + g_{Y_i}(X)U + d_i(X)$$
$$\dot{y}_{a_i} = f_{Y_i}(X) + g_{Y_i}(X)U + \hat{d}_i(X) + k_{a_i} e_{a_i}$$

From universal function approximation property

$$d_i(X) = W_i^T \varphi_i(X) + \varepsilon_i$$
$$\hat{d}_i(X) = \hat{W}_i^T \varphi_i(X)$$

Error dynamics

$$\dot{e}_{a_i} = d_i(X) - \hat{d}_i(X) - k_{a_i} e_{a_i}$$
$$= \tilde{W}_i^T \Phi_i(X) + \varepsilon_i - k_{a_i} e_{a_i}$$

Lyapunov Stability Analysis

Lyapunov Function Candidate:

$$L_i = \frac{1}{2}\left(e_{a_i} p_i e_{a_i}\right) + \frac{1}{2}\left(\tilde{W}_i^T \gamma_i \tilde{W}_i\right)$$

Derivative of Lyapunov Function:

$$\begin{aligned}\dot{L}_i &= e_{a_i} p_i \dot{e}_{a_i} + \tilde{W}_i^T \gamma_i \dot{\tilde{W}}_i \\ &= e_{a_i} p_i \left[\tilde{W}_i^T \Phi_i(X) + \varepsilon_i - k_{a_i} e_{a_i}\right] - \tilde{W}_i^T \gamma_i \dot{\hat{W}}_i \\ &= \tilde{W}_i^T \left[e_{a_i} p_i \Phi_i(X) - \gamma_i^{-1} \dot{\hat{W}}_i\right] + e_{a_i} p_i \varepsilon_i - k_{a_i} e_{a_i}^2 p_i\end{aligned}$$

0

Weight Update Rule:

$$\dot{\hat{W}}_i = \gamma_i e_{a_i} p_i \Phi_i(X, X_d)$$

Lyapunov Stability Analysis

This condition leads to $\dot{L}_i = e_{a_i} p_i \varepsilon_i - k_{a_i} e_{a_i}^2 p_i$

$\dot{L}_i < 0$ whenever $|e_{a_i}| > |\varepsilon_i| / k_{a_i}$

Using the Lyapunov stability theory, we conclude that the trajectory of e_{a_i} and $\tilde{W}_i$ are pulled towards the origin.

Hence, the output dynamics is “Practically Stable”!

Problem Specific equations

- Output vector in longitudinal mode:

$$Y \triangleq \begin{bmatrix} P & a_z & a_y & V_T \end{bmatrix}^T$$

- Output vector in lateral mode:

$$Y \triangleq \begin{bmatrix} P & Q & a_y & V_T \end{bmatrix}^T$$

Basis Function

$$\varphi_i(X) = \left[e^{-\frac{1}{2}\left(\frac{\|Y-Y_a\|^2}{\sigma_1^2}\right)} \quad e^{-\frac{1}{2}\left(\frac{\|Y-Y_a\|^2}{\sigma_2^2}\right)} \quad e^{-\frac{1}{2}\left(\frac{\|Y-Y_a\|^2}{\sigma_3^2}\right)} \right]^T$$

where mean values chosen were:

$$\sigma_1 = 0.1, \sigma_2 = 1, \sigma_3 = 10$$

Design parameters selected (Longitudinal mode)

- The learning rates and the scalar values:

$$\gamma_P = \gamma_{n_z} = \gamma_{n_y} = \gamma_{V_T} = 60$$

$$p_p = 0.0001, \quad p_{n_z} = 0.05, \quad p_{n_y} = 0.001, \quad p_{V_T} = 0.005$$

- The constants selected are:

$$K = diag\begin{bmatrix} 5 & 5 & 5 & 4 \end{bmatrix}$$

$$K_a = diag\begin{bmatrix} 0.05 & 0.05 & 0.05 & 1 \end{bmatrix}$$

Design parameters selected (Lateral mode)

- The learning rates and the scalar values:

$$\gamma_P = \gamma_{n_z} = \gamma_{n_y} = 60; \quad \gamma_{V_T} = 40$$

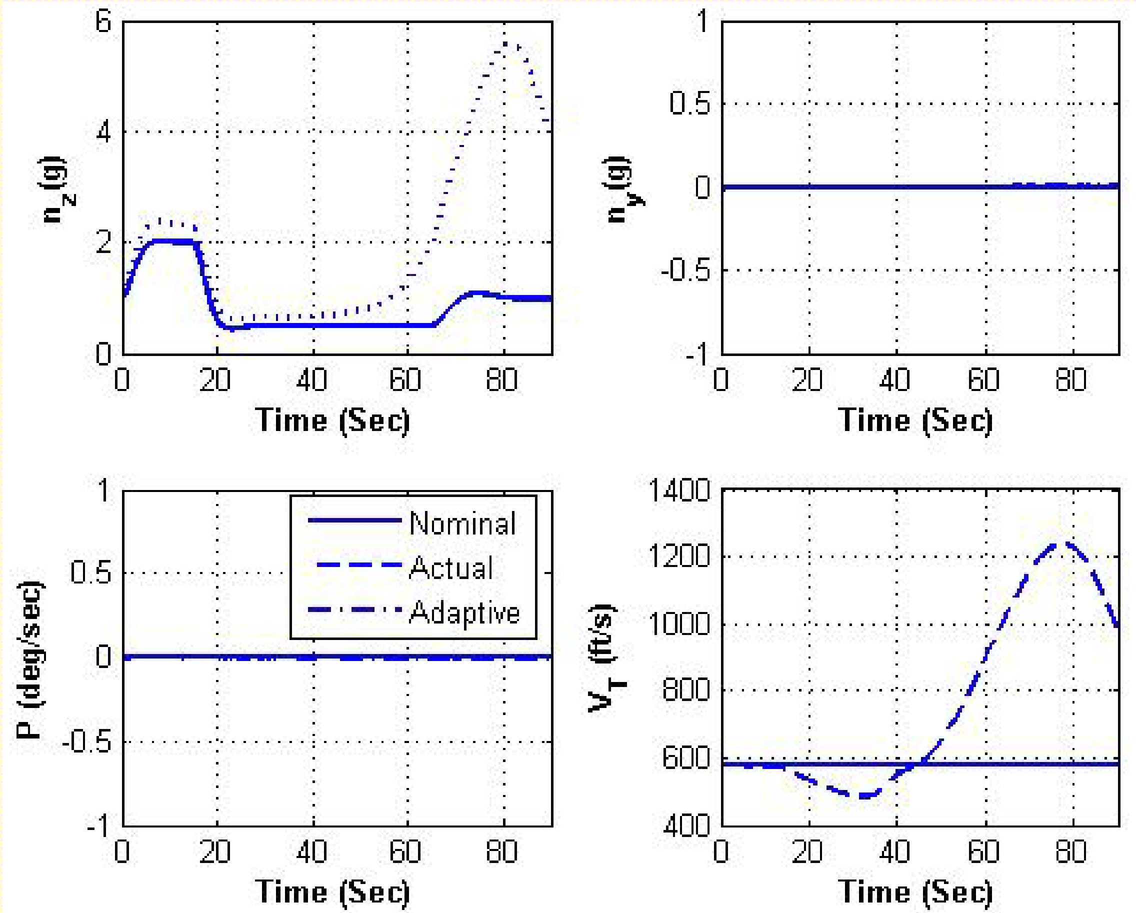
$$p_p = p_q = p_{n_y} = 0.0001, \quad p_{V_T} = 0.05$$

- The constants selected are:

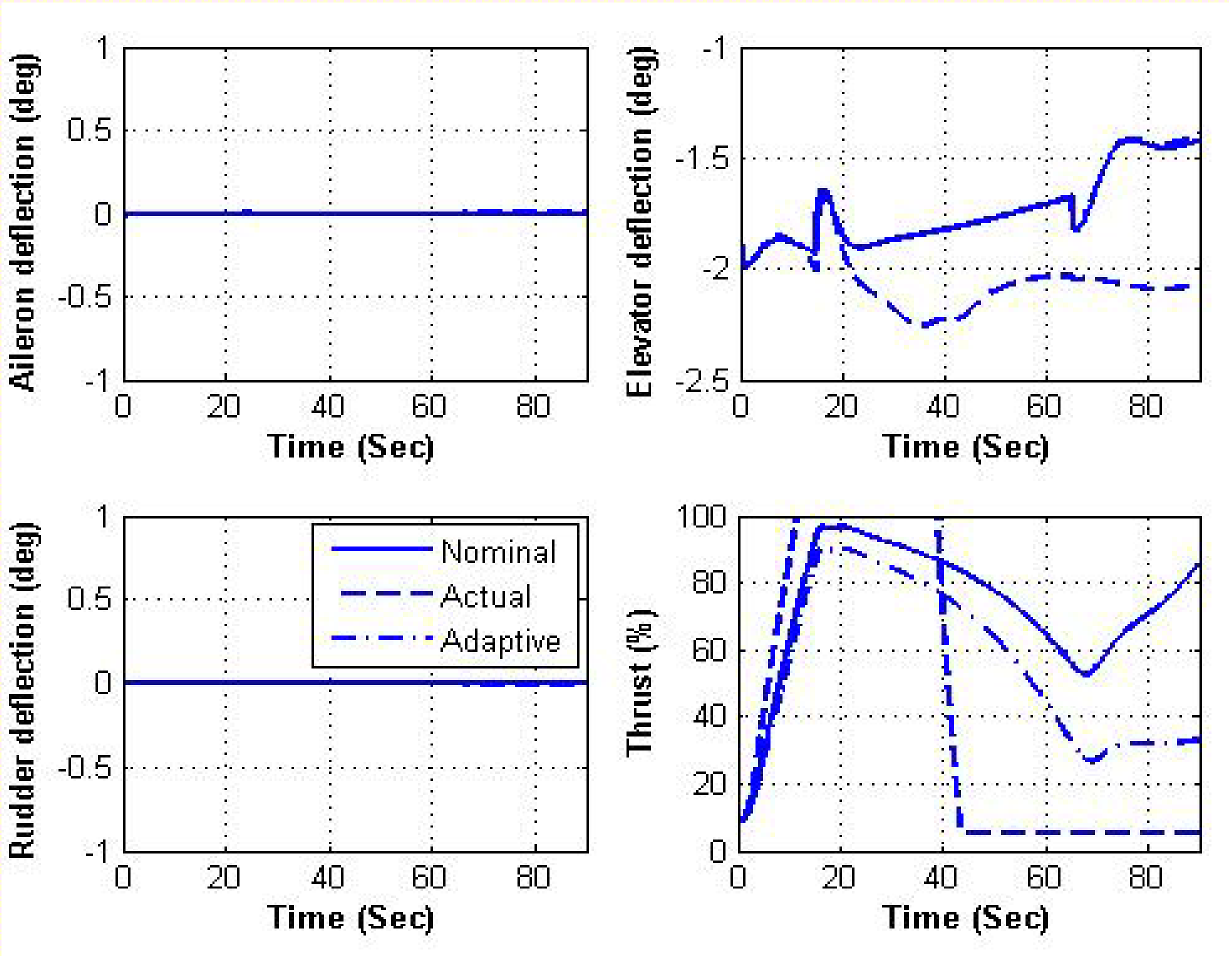
$$K = diag\begin{bmatrix} 5 & 4 & 4 & 4 \end{bmatrix}$$

$$K_a = diag\begin{bmatrix} 0.05 & 0.8 & 0.05 & 0.05 \end{bmatrix}$$

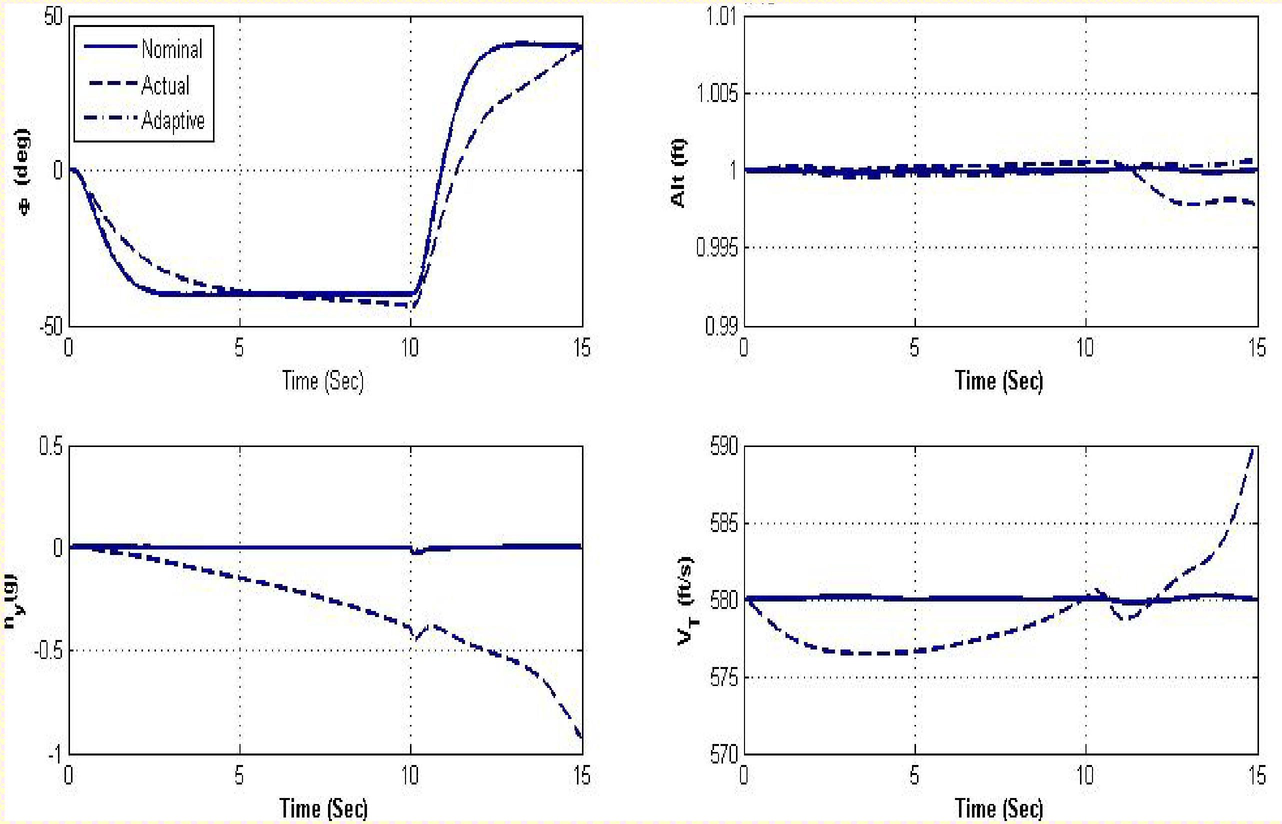
Outputs in Longitudinal Mode



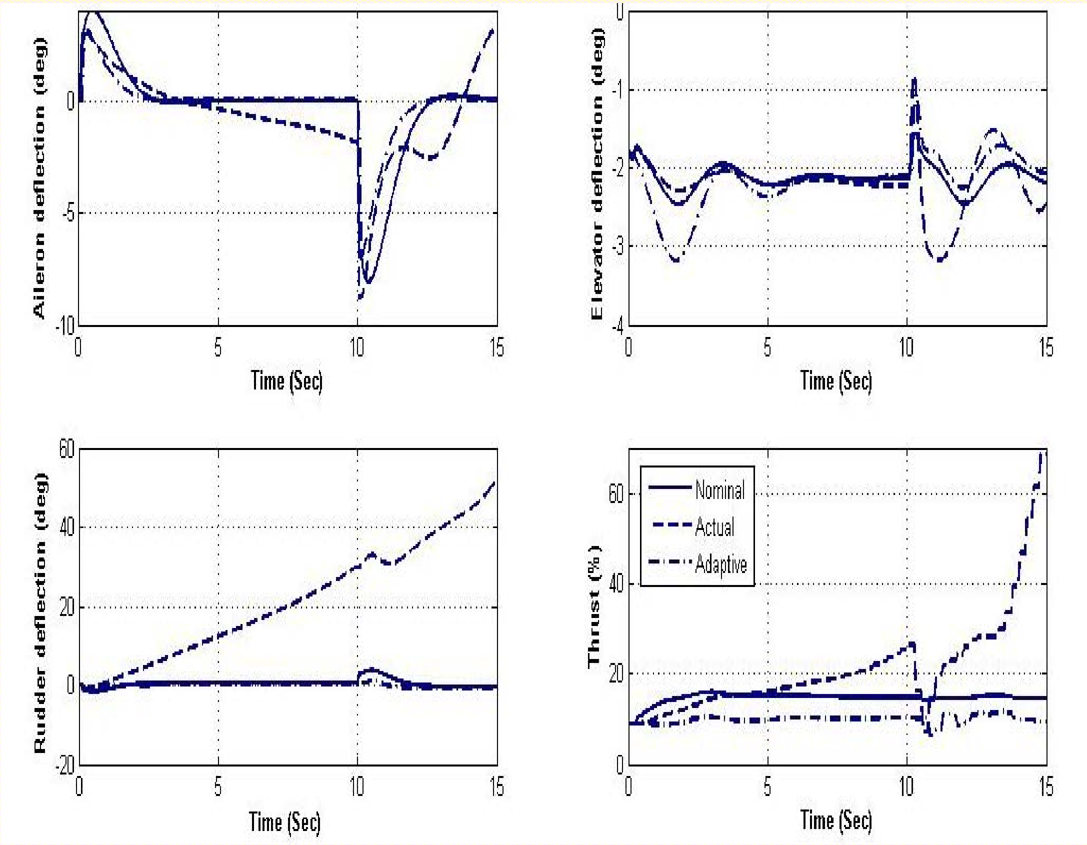
Controls in Longitudinal Mode



Outputs in Lateral Mode



Controls in Lateral Mode



Robustness Enhancement: Longitudinal Mode

Aerodynamic Coefficient Perturbation	1 %	1 %	2 %	2 %	5 %	5 %	10 %	10 %
Inertia Parameter Perturbation	5 %	10 %	5 %	10 %	5 %	10 %	5 %	10 %
Nominal Success	100 %	100 %	96 %	92 %	76 %	70 %	48 %	40 %
Adaptive Success	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %

Robustness Enhancement: Lateral Mode

Aerodynamic Coefficient Perturbation	1 %	1 %	2 %	2 %	5 %	5 %	10 %	10 %
Inertia Parameter Perturbation	5 %	10 %	5 %	10 %	5 %	10 %	5 %	10 %
Nominal Success	100 %	100 %	100 %	100 %	98 %	94 %	76 %	76 %
Adaptive Success	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %

Summary

- Nominal control design has been carried out using "dynamic inversion" (the new method shows remarkable improvement in performance!)
- The nominal design has been augmented with "neuro-adaptive design" for improvement in robustness.
- Simulation Results
  - Tracking performance is very good
  - Enhancement of robustness is substantial

References

- **Radhakant Padhi**, Narayan P. Rao, Siddharth Goyal and Abha Tripathi, "*A Model-Following Neuro-Adaptive Approach for Robust Control of High Performance Aircrafts*", Automatic Control in Aerospace, Vol. 3, No. 1, May 2010.
- **Radhakant Padhi** and S. N. Balakrishnan, *"Implementation of Pilot Commands in Aircraft Control: A New Dynamic Inversion Approach",* AIAA Conference on Guidance Navigation and Control, 2003, Austin, TX, USA.
- **Radhakant Padhi**, Nishant Unnikrishnan and S. N. Balakrishnan, "*Model Following Neuro-Adaptive Control Design for Non-square, Non-affine Nonlinear Systems*", IET Control Theory and Applications, Vol. 1 (6), Nov 2007, pp.1650-1661.

Thanks for the Attention...!