Robust Control Systems Research with Applications

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THANKS TO FERMI-LABS FOR THE INVITATION AND HOSPITALITY

In particular to Dr. Aseet Mukherjee and Dr. Steve Holmes

Outline

- Introduction and Perspective on Control Systems Field
- Uncertainty and Robustness: Time Domain State Space and Frequency Domain Transfer Function Viewpoints
- Robust Control Design Methods with Applications
- Overview of OSU Robust Control Group Research
- Fault Diagnostics and Control Design for Fault Tolerance
- Distributed Control with Communication Constraints
- Control of Superconducting Cavities: Relevance and Applicability of our research
- Conclusions and Future Research
- Possible Avenues of Research Collaboration with FermiLabs

Introduction and Perspective

Control System

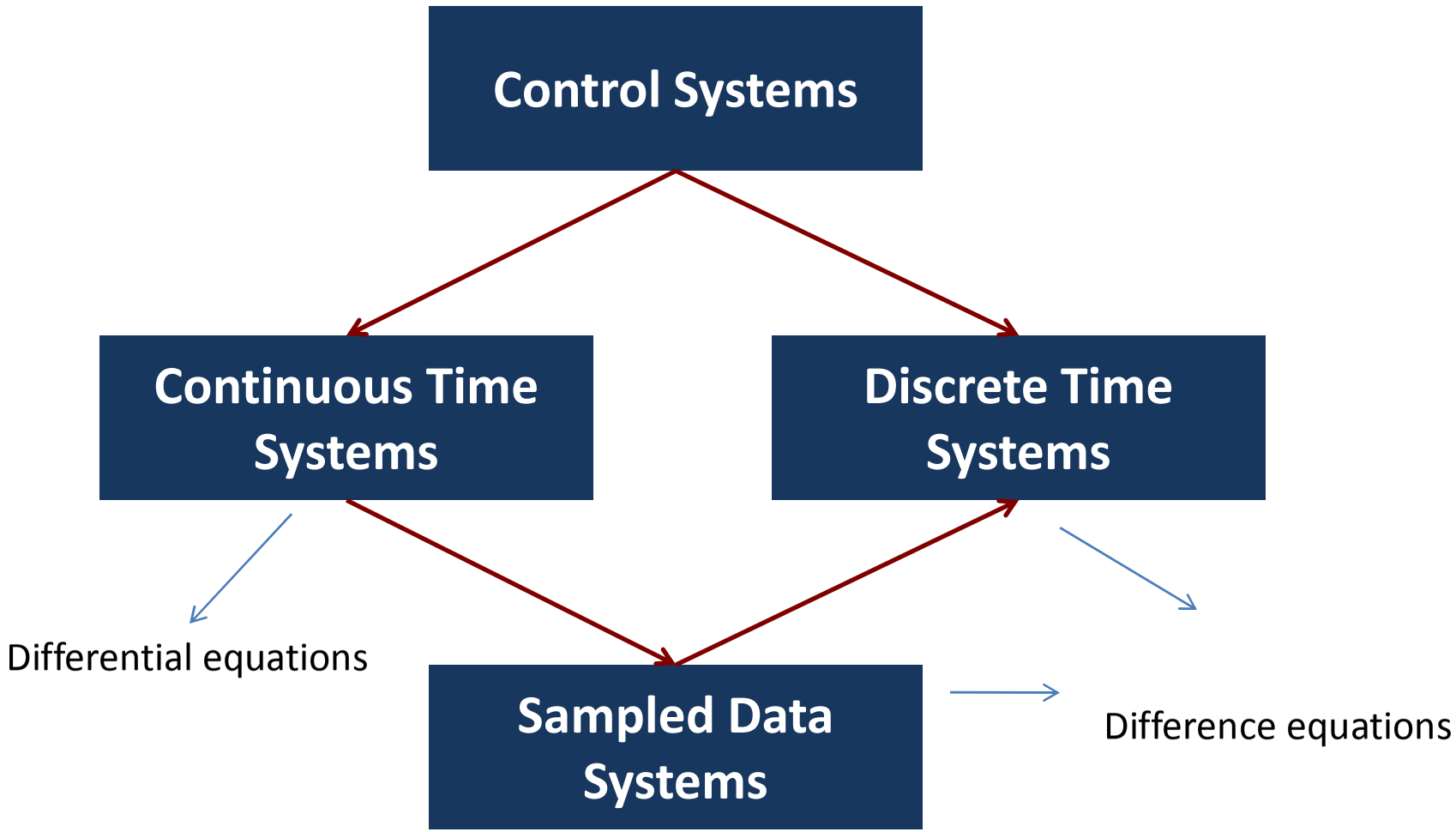
Time Domain State Space Representation

$$\dot{x} = Ax + Bu + Hw$$
$$y = Cx + Du$$
$$z = Mx$$

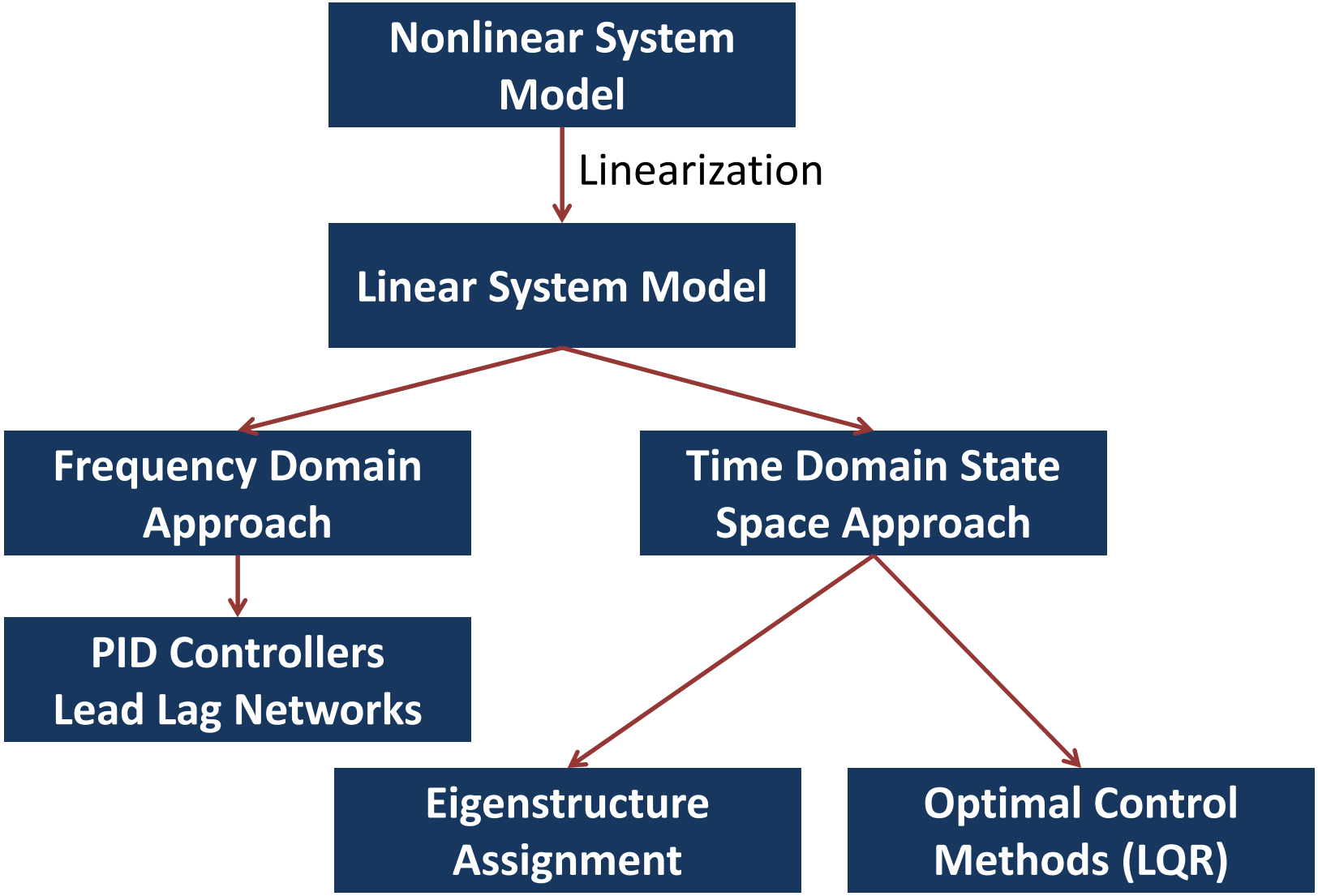
Frequency Domain Transfer Function Representation

$$G(s) = \frac{N(s)}{D(s)}$$

Control Systems Modeling



Standard Controller Design Methodologies



Uncertainty and Robustness in Control Systems

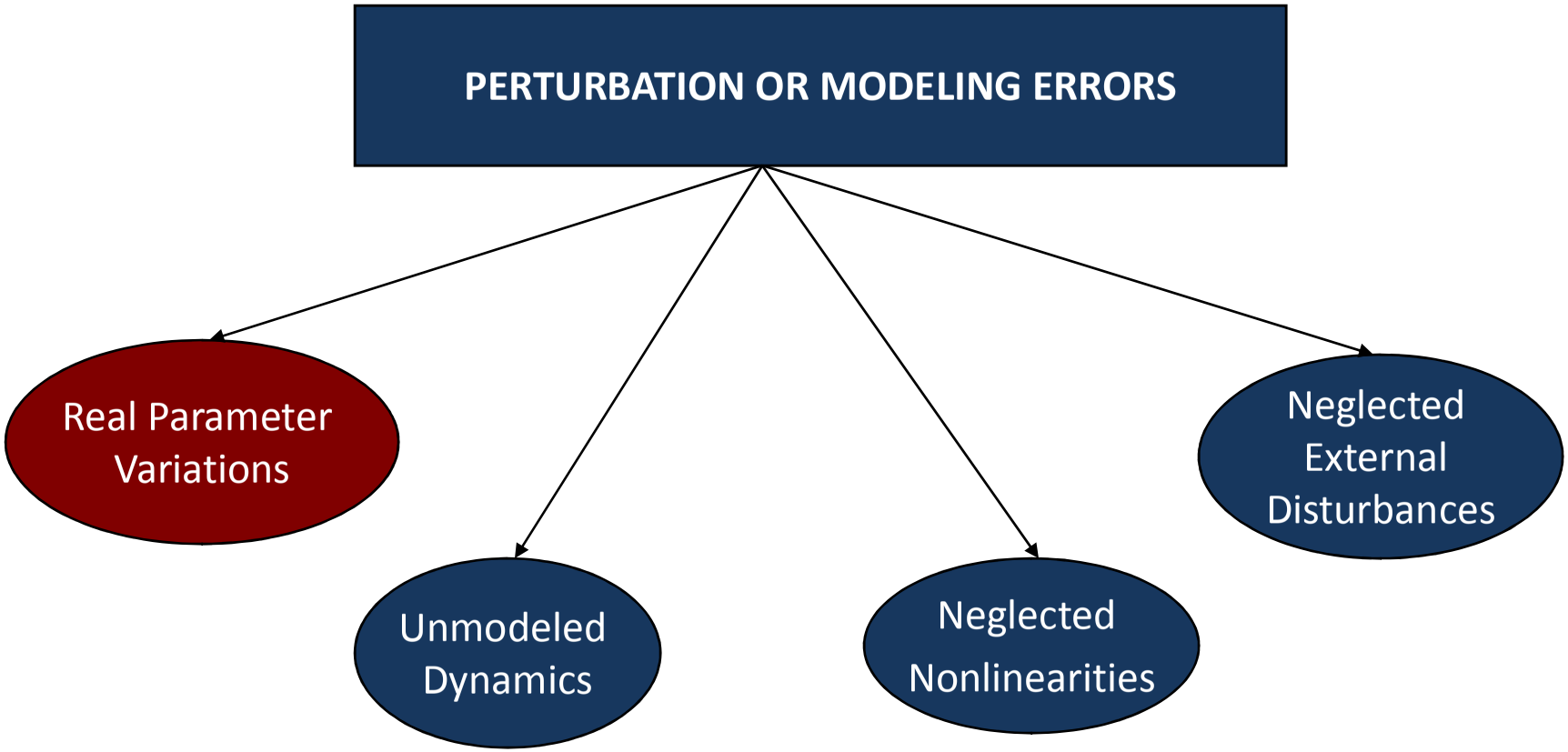
Uncertainty: Inevitable in real life problems

Accommodating uncertainty is important

Robustness: A necessary feature in Analysis and Design of feedback Control Systems

Main theme of our research

Uncertainty Characterization



Uncertainty Characterization

- Real Parameter Variations

⇩

Time Domain (State Space) ⇩ Matrix Variations	⇔	Frequency Domain (Transfer Function) ⇩ Polynomial Variations

- Unmodeled Dynamics

⇩

Time Domain ??? ???	⇔	Frequency Domain

$$G_0(s) + \Delta G(s)$$

$$\|\Delta G(s)\| < |r(s)|$$

Unstructured Uncertainty (Norm Bounded)

Time Domain
(State Space)

$\Downarrow$

$A_0 + E$

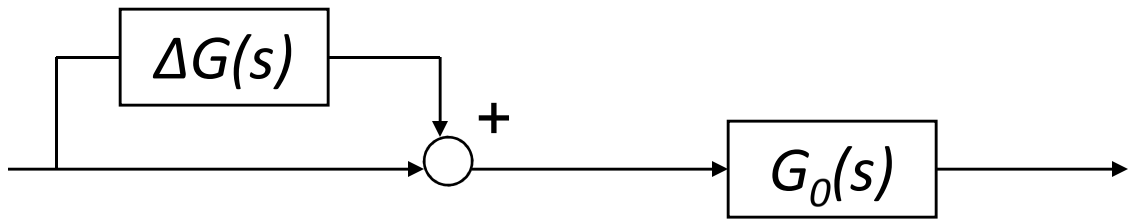
$||E|| < r$

Frequency Domain

$\Downarrow$

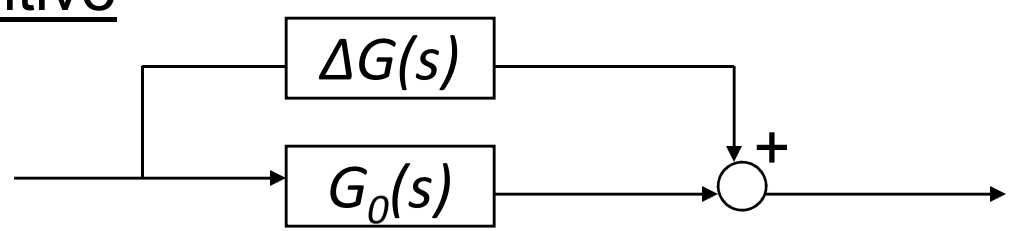
$||\Delta G(j\omega)|| < r(j\omega)|$

<u>Multiplicative</u>



$$G(s) = G_0(s)\,[\,I + \Delta G(s)\,]$$

<u>Additive</u>



$$G(s) = G_0(s) + \Delta G(s)$$

Structured Uncertainty

Time Domain
(State Space)

$$\Downarrow$$

$$A_0 + E(q)$$

$$\underline{q}_i < q_i < \overline{q}_i$$

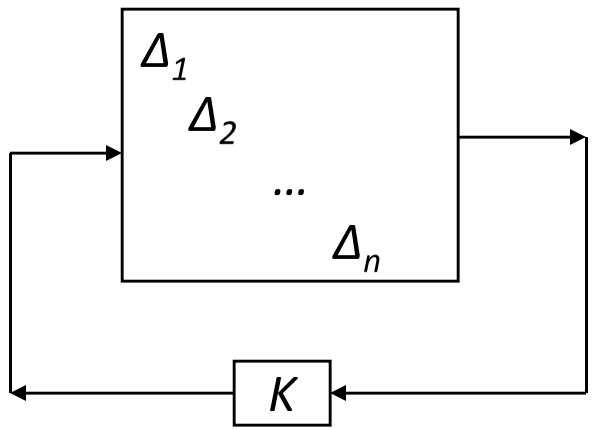
$$\Downarrow$$

$$A_0 + \sum_{i=1}^{r} q_i E_i$$

Real Structured Uncertainty

Frequency Domain
(Transfer Function)

(1)



Complex Structured Uncertainty

(2)

$$P(s, q) = N(s, q)/D(s, q)$$

$$\Downarrow$$

Real Structured Uncertainty

Structured Uncertainty

Time Domain
(State Space)

$$\Downarrow$$

$$A_0 + E(q)$$

$$\underline{q}_i < q_i < \overline{q}_i$$

$$\Downarrow$$

$$A_0 + \sum_{i=1}^{r} q_i E_i$$

Real Structured
Uncertainty

E(t) $\Longrightarrow$ Time varying uncertainty

$\Downarrow$

Lyapunov Matrix Theory Approach

E=constant $\Longrightarrow$ Time invariant uncertainty

$\Downarrow$

Kronecker Matrix Theory Approach

System Specifications

STABILITY (Fundamental) ⇒ Stability Robustness

⇓

Open Left Half Plane

PERFORMANCE

- Transient Response
- Steady State Response
- Tracking & Regulation
- Disturbance Rejection

⇒ Performance Robustness

⇓

D-stability and Eigenstructure Assignment

Major Approaches

	Approach	Uncertainty Category	Contributors
(1)	μ-Synthesis (Structured Singular Value , Multivariable Stability regions)	Structured and Unstructured (Frequency domain)	Tits, Safonov and Colleagues
(2)	Quantitative feedback Control	Structured frequency Domain	Horowitz, Nwokah, Wie and Colleagues
(3)	H_2 Theory (LQG/LQR)	Unstructured Frequency Domain	Athans, Stein, Bernstein, Haddad, and Colleagues

Major Approaches

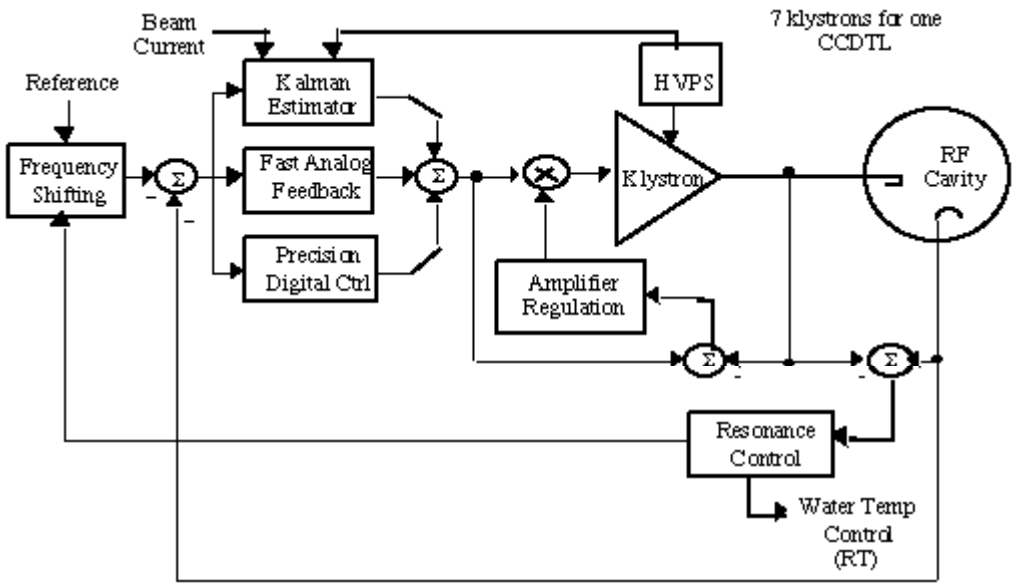
	Approach	Uncertainty Category	Contributors
(4)	H_2/ H_∞ H-inf Theory	Unstructured Frequency domain	Zames, Glover, Francis, Tennenbaum and Colleagues
(5)	Kharitonov based Polynomial methods	Structured, real Parameter Transfer Function based	Kharitonov, Barmish, Bhattacharya, Acermann, Bose and Colleagues
(6)	Lyapunov Kronecker based Matrix Methods	Structured, real Parameter, Time domain	Yedavalli, Qiu &Davison, Juang, Hinqich & Ritchard, Barmish and Colleagues
(7)	Mixed H_2/ H_∞ Theory	Combined Uncertainty, State Space	Bernstein & Haddad, Banda, Khargonekar, and Colleagues

Literature in the Field

Many contributions by other researchers are covered in various books and monographs: One relevant and useful reference is

"*Recent Advances in Robust Control*" Edited by Peter Dorato and R.K. Yedavalli, IEEE Press, 1990

LLRF Control Systems



Block diagram of the LLRF control system.

- Amplitude Control
- Phase Control

- Significant Literature and Interest in Europe and Asia and our US Govt Labs

Nominal SNS RF Control System

- Los Alamos and Oak Ridge labs are active in RF Control Systems Research
- A Linear Klystron model around each operating point can be obtained
- An SRF Cavity linear model can be obtained by equivalent circuit of the cavity (as an RF generator with a transmission line) approach.

Nominal RF Control System Modeling

- State variables: Complex Cavity Voltage Real and Imaginary parts
- Control Variables: Generator Current Real and Imaginary parts
- Matlab and Simulink can be used to simulate the control system behavior

Important to consider Perturbations and accommodate them in control design

Uncertainty Characterization in LINAC LLRF Control

- Uncertainty in RF components (like RF switch, directional coupler etc) and cabling: to be modeled as multiplicative uncertainty

- High Voltage Power supply ripple to be modeled as additive disturbance

- Lorentz force detuning frequency and microphonics can be modeled as time varying, real uncertain parameters

- Beam current I is modeled as a time invariant real uncertain parameter within a bounded set.

Perturbation modeling in RF Control Systems

- 4 μ second delay observed in RF Control Systems of TESLA Test Facility

- Time delay increases the phase shift between input and output signals and thus limits the maximum allowable gain.

All these perturbations cause phase and amplitude distortions.
We need to design controllers which are robust to these Perturbations.

Both Time Domain State Space and Frequency Domain approaches need to be pursued.

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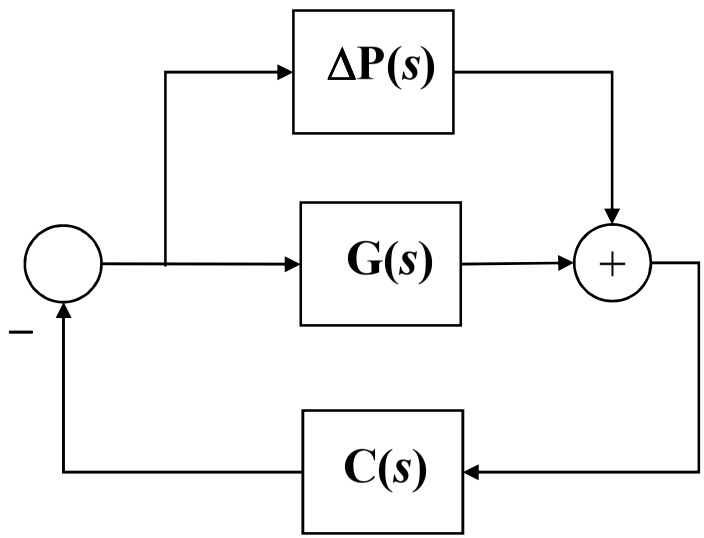
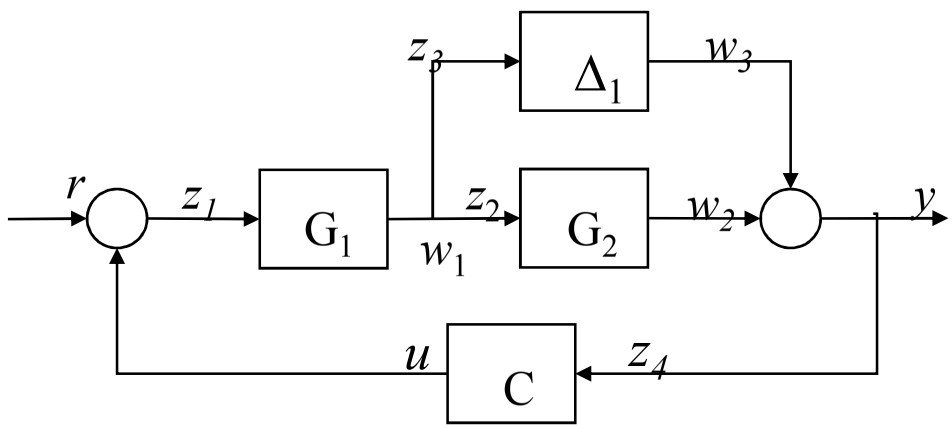
Robust Control Design Methods

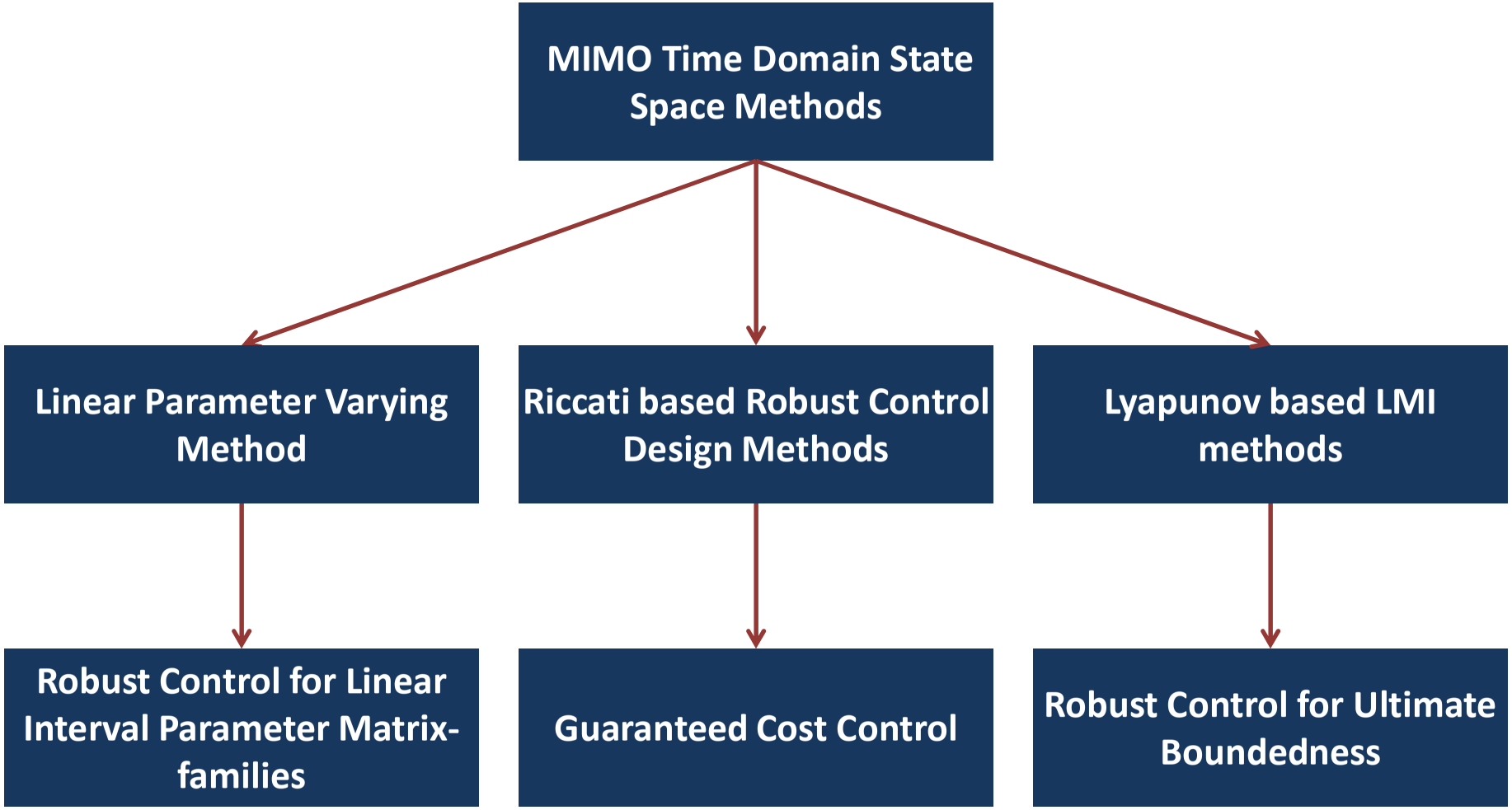
MIMO Frequency Domain Methods

- H_∞ Loop Shaping Method
- μ-synthesis Method



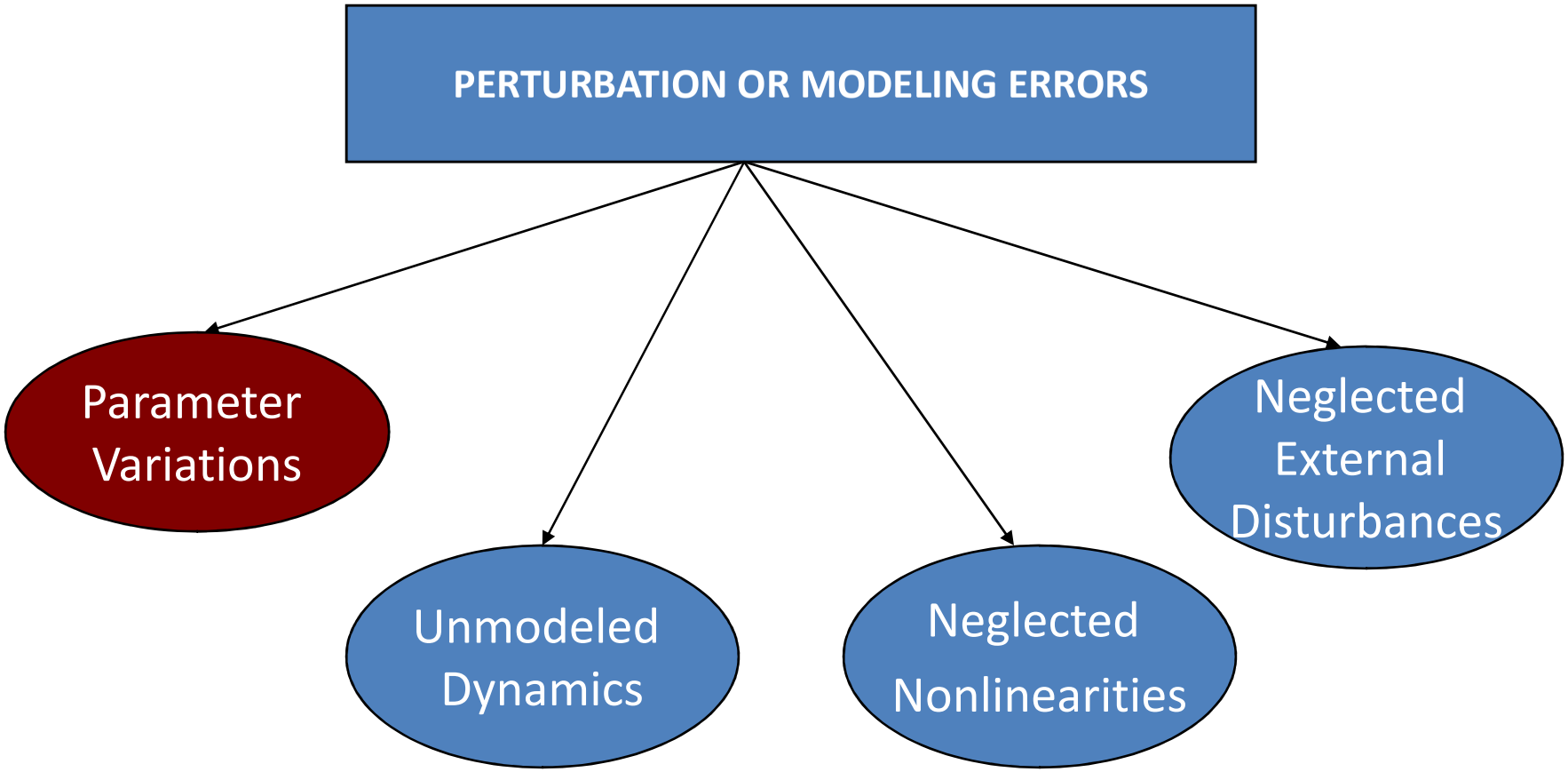


Robust Control Design Methods



Robust Control of Linear Interval Parameter Systems in State Space framework

Uncertainty Characterization



Linear State Feedback Control Design Using Perturbation Bound Analysis

Consider the system

$$\dot{x} = Ax + Bu$$

$$y = Cx$$

with the control law given by

$$u = Gx$$

Let us assume that we can determine a G such that the nominal closed loop system matrix A+BG is stable.

Perturbation Bound Analysis

Let us assume perturbations in the A and B matrices with the following structure:

$$\Delta A = \in_a U_{ea}$$

$$\Delta B = \in_b U_{eb}$$

where $\in_a$, and $\in_b$ denote the maximum absolute deviations expected in the matrices A and B, and the matrices U_{ea} and U_{eb} capture the structure of the uncertainty.

Total perturbationin linear closed loop system matrix of the system with nominal control of $u = Gx$ is given by

$$\Delta = \Delta A + \Delta B G_m = \in_a U_{ea} + \in_b U_{eb} G_m$$

Perturbation Bound Analysis

Theorem :

The perturbed linear system is stable for all perturbations bounded by $\in_a$ and $\in_b$ if

$$\in_a < \frac{1}{\sigma_{\max}[P_m(U_{ea} + \overline{\in} U_{eb} G_m)]_s} = \mu$$

and

$$\in_b < \overline{\in}_\mu \ \mu$$

where P is the solution of the Lyapunov matrix equation

$$P(A+BG) + (A+BG)^T P + 2I_n = 0$$

Stability Robustness Index and Control Design Algorithm

Define

Stability Robustness Index β_{SR} as follows:

Case a) Checking stability for given perturbation range:

For this case

$$\beta_{SR} \overset{\Delta}{=} \mu - \in_a$$

Case b) Specifying the bound: For this case

$$\beta_{SR} \overset{\Delta}{=} \mu$$

Stability Robustness Index and Control Design Algorithm

Build a control gain via LQR method:

$$G = -\frac{1}{\rho_c} R_0^{-1} B^T K$$

$$KA + A^T K - KB \frac{R_0^{-1}}{\rho_c} B^T K + \overline{Q} = 0$$

Let the control gain G be varied via a scalar measure given by

$$J_{en} = \|G\|_s = \sigma_{\max}(G)$$

or

$$J_{en} = [\int_0^\infty (u^T u) dt]^{1/2} = [\int_0^\infty (x^T G^T G x) dt]^{1/2}$$

Plot β_{SR} v.s. J_{en} and select a gain which keeps β_{SR} positive and/or maximum

Application to Flight Control

Application to Vertical Takeoff and Landing Aircraft

$$\dot{x} = (A + \Delta A)x + (B + \Delta B)u \qquad x(0) = x_0$$

The components of state vector $x \rightarrow$ R^4 and control vector $u \rightarrow R^2$ are given by

$x_1 \rightarrow$ horizontal velocity(knots)

$x_2 \rightarrow$ vertical velocity(knots)

$x_3 \rightarrow$ pitch rate(degree/second)

$x_4 \rightarrow$ pitch angle(degrees)

$u_1 \rightarrow$ "collective" pitch control

$u_2 \rightarrow$ "longitudinal cyclic" pitch control

Application to Flight Control

$$A = \begin{bmatrix} -0.0366 & 0.0271 & 0.0188 & -0.4555 \\ 0.0482 & -1.01 & 0.0024 & -4.0208 \\ 0.1002 & 0.3681 & -0.707 & 1.4200 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.4422 & 0.1761 \\ 3.5446 & -7.5922 \\ -5.52 & 4.49 \\ 0 & 0 \end{bmatrix}$$

The initial condition is

$$x^T(0) = [0.85 \quad 0.15 \quad 0 \quad -0.05]$$

Example

$$0.3545 \le \overline{a}_{32} = 0.3681 \le 0.3817$$

$$1.31 \le \overline{a}_{34} = 1.42 \le 1.53$$

$$3.39 \le \overline{b}_{21} = 3.544 \le 3.702$$

Case I

$|\Delta a_{32}| = 0.1363$ $\quad$ $|\Delta a_{34}| = 1.106$ $\quad$ $|\Delta b_{21}| = 1.5674$

Case II

$|\Delta a_{32}| = 0.0136$ $\quad$ $|\Delta a_{34}| = 0.11$ $\quad$ $|\Delta b_{21}| = 0.157$

Example

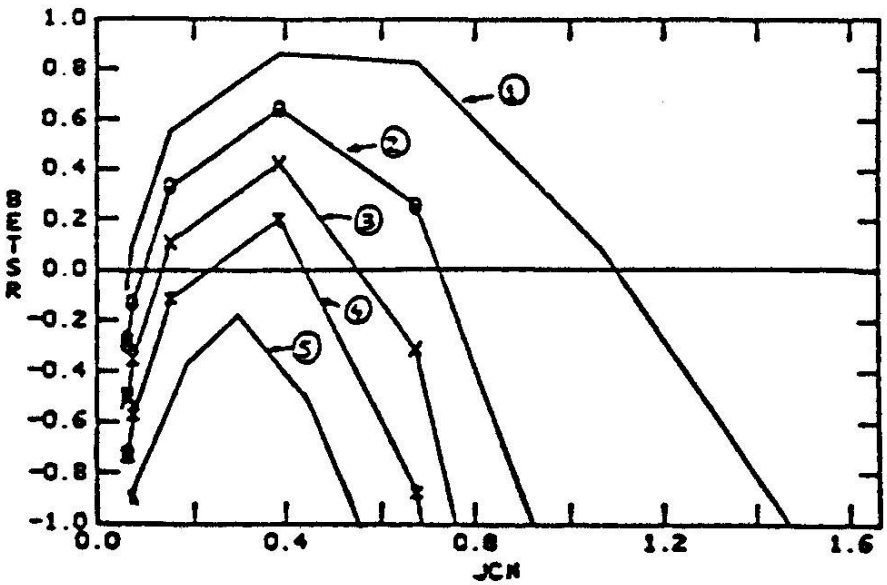


Fig. 1. Variation of β_{SR} with nominal control effort $J_{cn}(\Delta A \neq 0, \Delta B \neq 0)$.

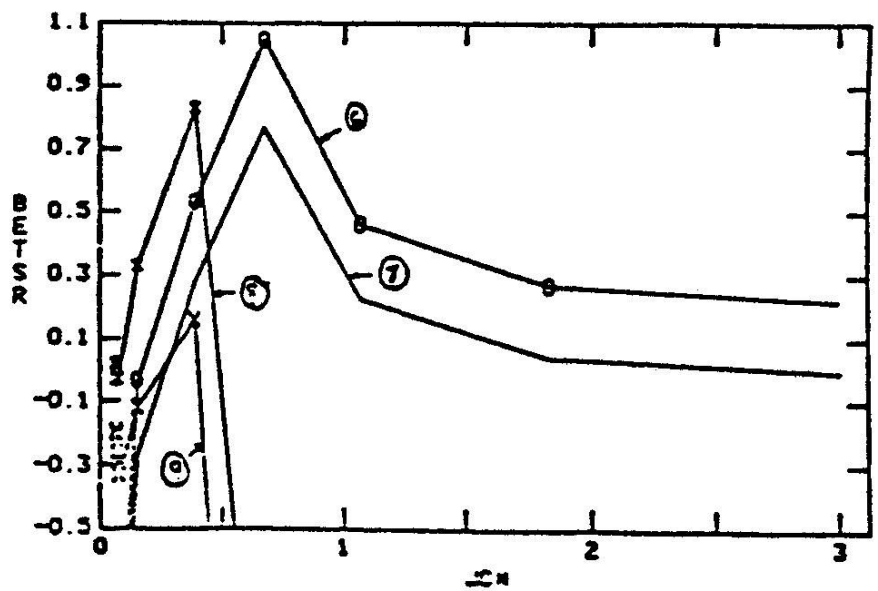
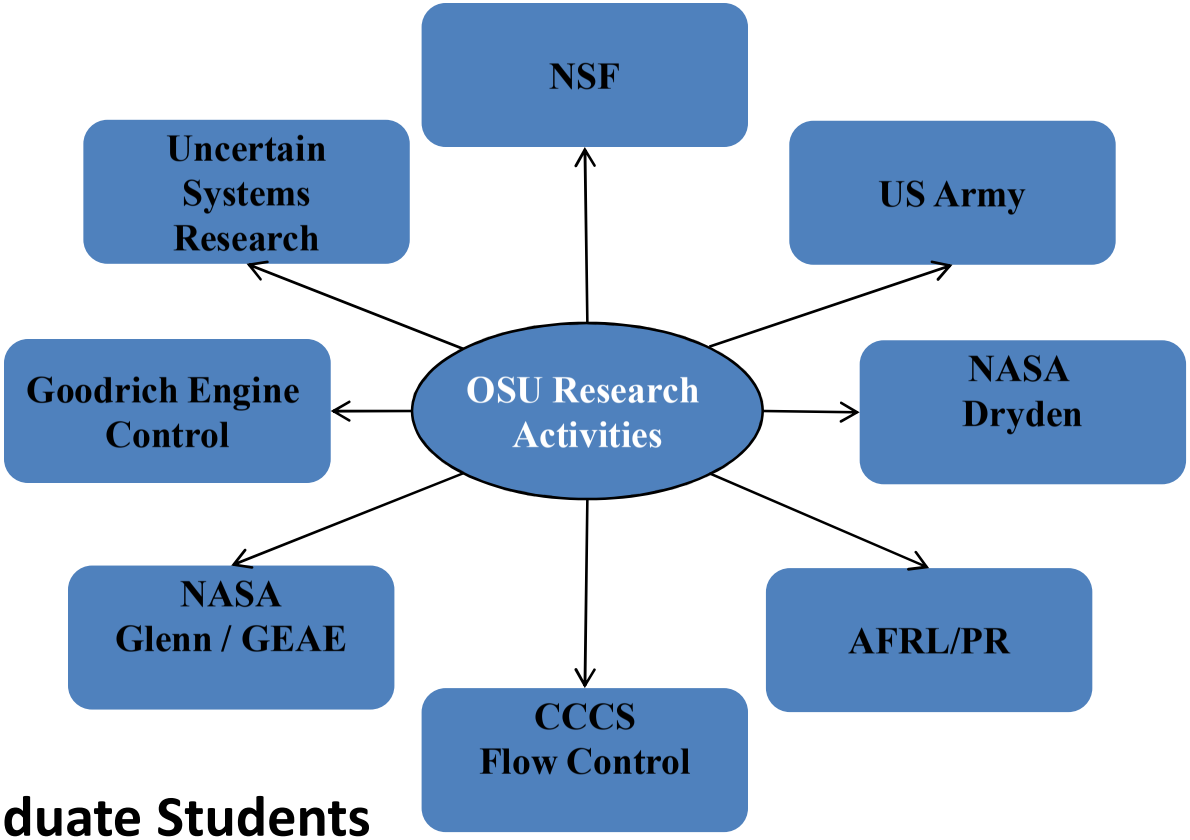


Fig. 2. Variation of β_{SR} with nominal control effort $J_{cn}(\Delta A = 0, \text{ or } \Delta B = 0)$.

OSU Robust Control Group Research



Current Graduate Students

- Wenfei Li (M.S./Ph.D.)
- Hsun-Hsun Huang (Ph.D.)
- Nagini Devarakonda (Ph.D.)
- Rohit Belapurkar (M.S./ Ph.D)

OSU Robust Control Group Research

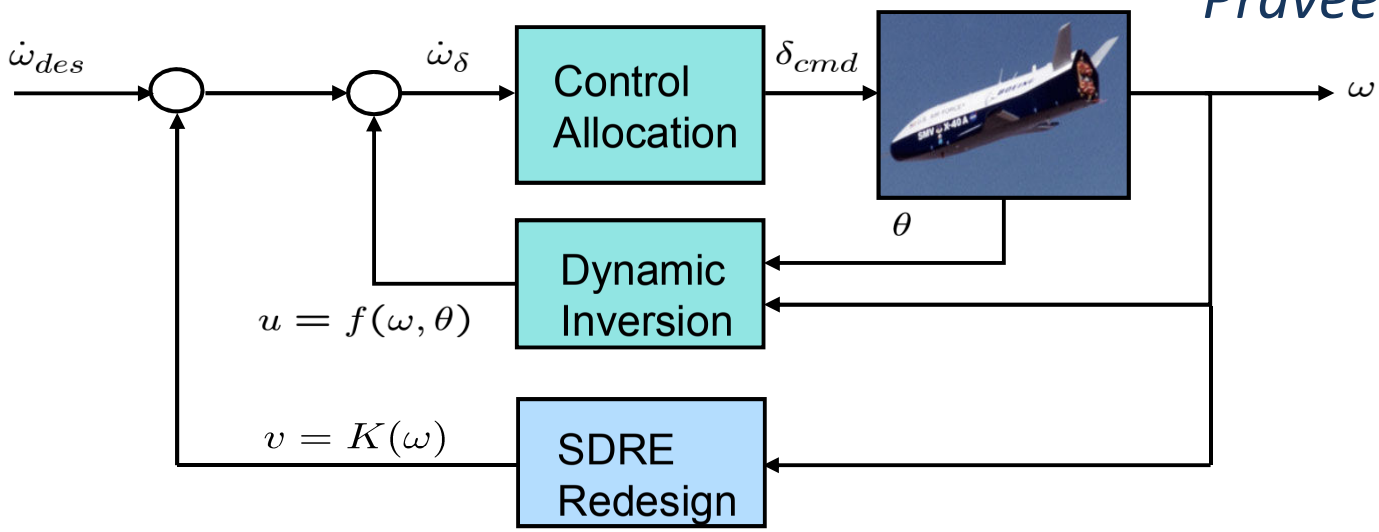
- H-Inf control with Regional Stability Constraints (Liu and Yedavalli)
- Time response bounds for Linear Uncertain systems (CR Ashok Kumar and Yedavalli)
- Stability and Robustness for Matrix Second Order Systems with smart structure control applications (Anjali Diwekar and Yedavalli)
- Control Design in Reciprocal State Space Framework (Tseng and Yedavalli)
- Smart Deformable Wing structures for Improved Aircraft Roll Over maneuvers (Kwak and Yedavalli)

OSU Robust Control Group Research

- Neural network based nonlinear controllers for flight vehicle applications (Shankar and Yedavalli)
- Fault detection using dynamic threshold approach with aircraft engine applications (Li and Yedavalli)
- Robust stability and control of multi-body ground vehicles under uncertainty and failures (Huang and Yedavalli)
- Ecological sign stability and its use in robust engineering systems (Devarakonda and Yedavalli)
- Distributed engine control under communication constraints (Belapurkar and Yedavalli)

X-40 Dynamic Inversion Controller

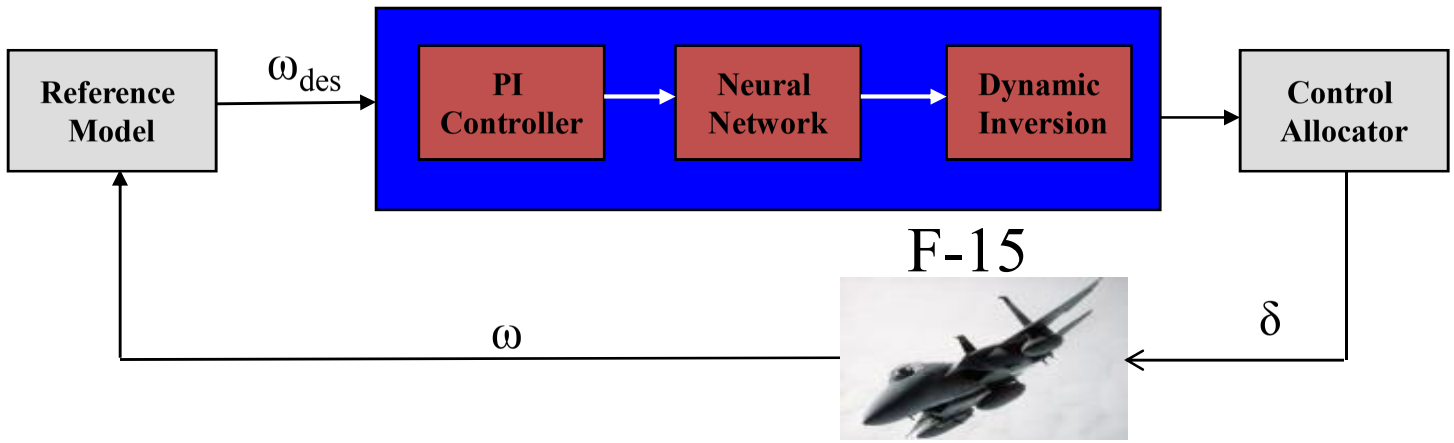
Praveen Shankar



- Robustness Analysis of the X-40A Dynamic Inversion Controller
- Implementation of combined Dynamic Inversion - State Dependent Riccati Equation Technique
- Stability Domain Estimation (Region of Attraction)
  - Method of Vector Norms
  - Sum of Squares Programming

A Neural Network Based Adaptive Observer for Turbine Engine Parameter Estimation

Praveen Shankar

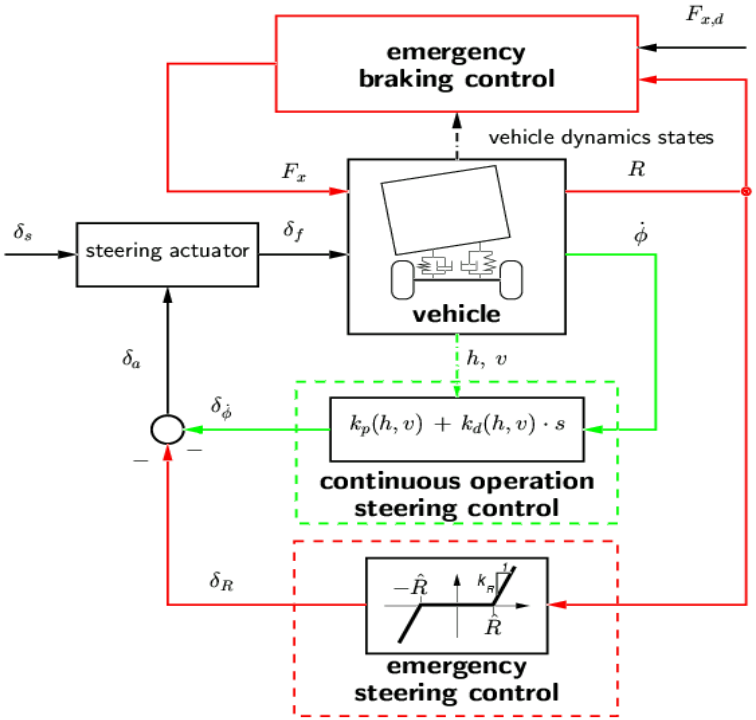


- Implementation of Growing Radial Basis Function Neural Network to minimize error due to modeling and failures in control surfaces
- Successfully implemented for F-15 Dynamic Inversion Controller and F-18 Robust LQR Tracker
- To be implemented on piloted simulation at NASA Dryden

Robust Stability and Control of Multi-body Ground Vehicles

Hsun-Hsun Huang

- Robust Stability and Control of Multi-body Ground Vehicles under Uncertainty and Failures
- Ground Vehicle Dynamics
  - Rollover stability
  - Ride and Handling Performance
  - Stability under failures
- Efforts to Collaborate with TARDEC in Warren, MI

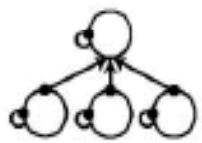


Qualitative (Sign) Stability of Ecology

Nagini Devarakonda

- Application of concepts of biology and life science to engineering systems: Qualitative (sign) stability and Robust stability

model a′



$$\mathbf{A}_{a'} = \begin{bmatrix} - & + & + & + \\ - & - & 0 & 0 \\ - & 0 & - & 0 \\ - & 0 & 0 & - \end{bmatrix}$$

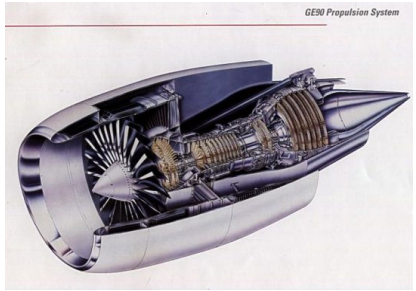
model b′

$$\mathbf{A}_{b'} = \begin{bmatrix} - & + & + & + \\ - & - & + & + \\ - & - & - & + \\ - & - & - & - \end{bmatrix}$$

Fault Diagnostics for Aircraft Engines With Uncertain Model Data

Wenfei Li

- Application of model based control strategies for engine control
- Application of model based diagnostic techniques
  - Sensor fault detection and isolation in Turbine Engine simulation model using Neural Networks and bank of Kalman Filters
- Application of model based prognostic techniques to Turbine Engine simulation model



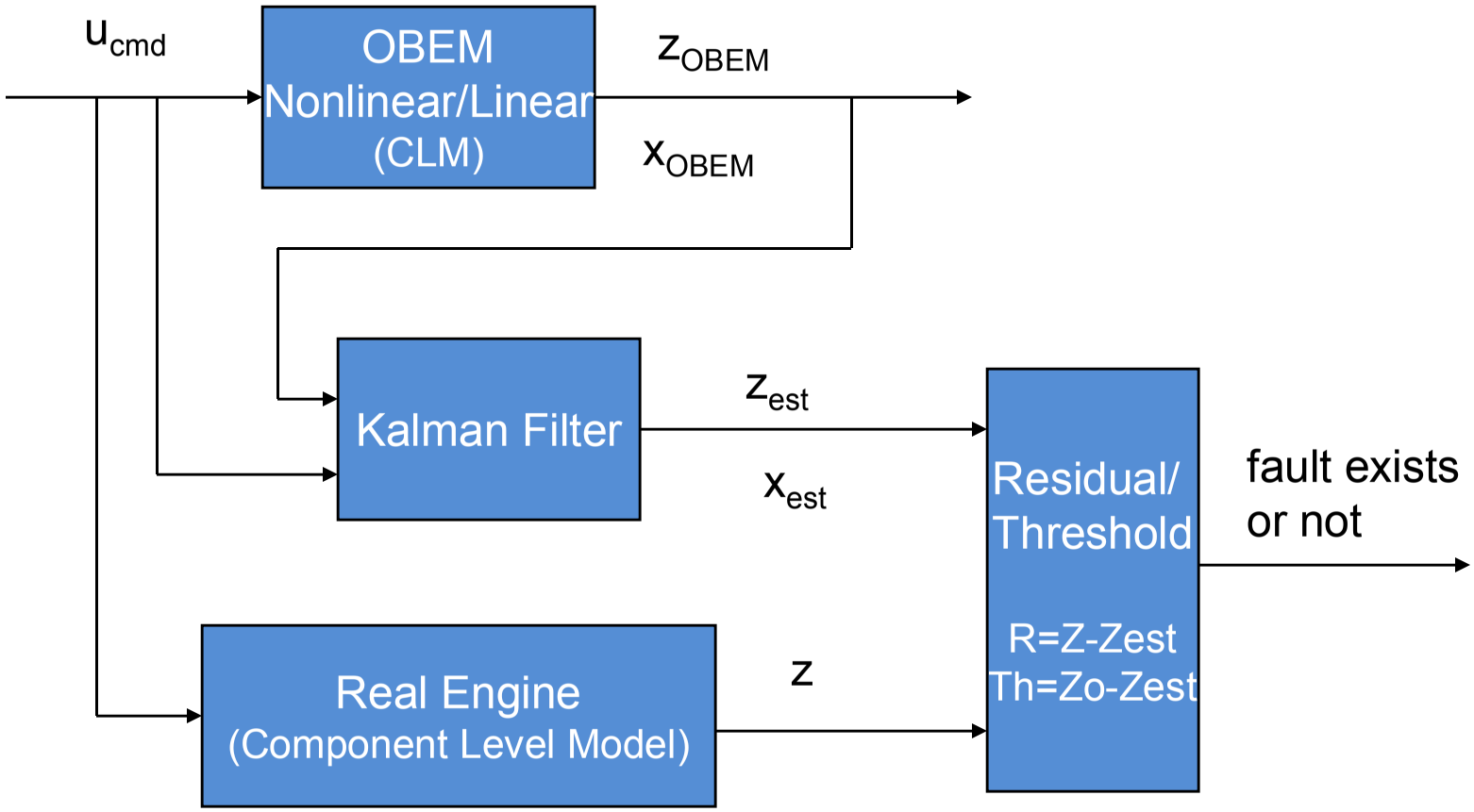
Kalman Filter Approach

- The Kalman filter is composed of a nonlinear on-board engine model (OBEM) and linear state-space model.
- The OBEM is to generate the state variables and sensor outputs, running in parallel with the actual engine at the estimated health condition.

Dynamic (Adaptive) Threshold

- Current approaches use Constant Threshold
  - Lacking guidelines for optimal threshold selection
  - Inappropriate Threshold selection leads to more False Alarms and Missed Detections
- Dynamic (Adaptive) Threshold Approach
  - Accommodates uncertainty in the Models
  - Helps in Reducing False Alarms and Missed Detections
  - Idea already used in Automotive applications

Fault Detection System using Dynamic Threshold Approach



Engine Fault Detection System Scheme

Engine System Model

- An aircraft engine is a nonlinear model:

$$\begin{cases} \dot{x} = f(x, h, u) + w \\ z = g(x, h, u) + v \end{cases}$$

where x, h, u and z represent state variables, health parameters, control command inputs, and sensor outputs. w is the process noise and v is the sensor noise.

Engine System Model

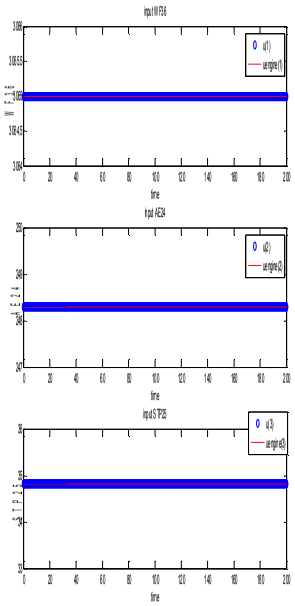
- Obtaining a linear state-space model at the desired steady-state point:

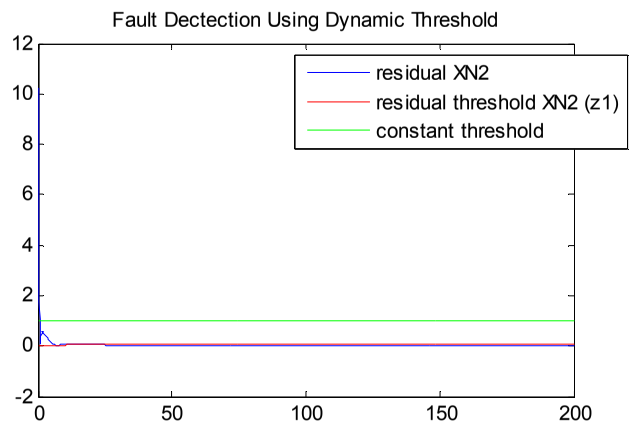
$$\begin{cases} \dot{x} = Ax + B(u + w) \\ z = Cx + v \end{cases}$$

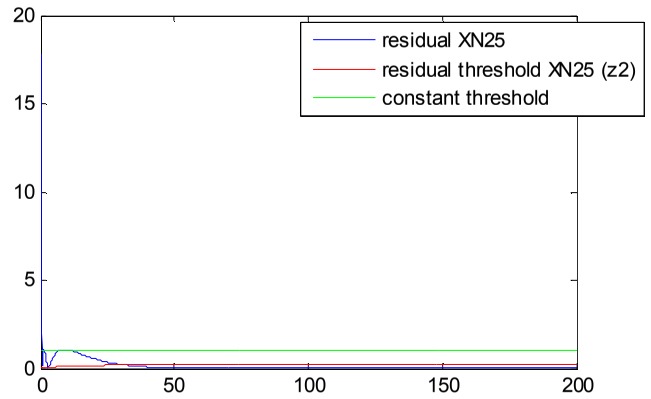
- Discretizing the linear continuous-time system for designing the Kalman filter:

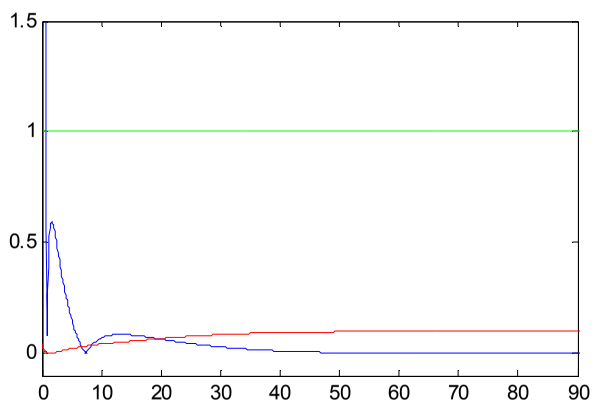
$$\begin{cases} x(k+1) = \Phi(k+1,k)x(k) + \Psi(k+1,k)u(k) + w_d(k) \\ z(k+1) = C(k+1)x + v(k+1) \end{cases}$$

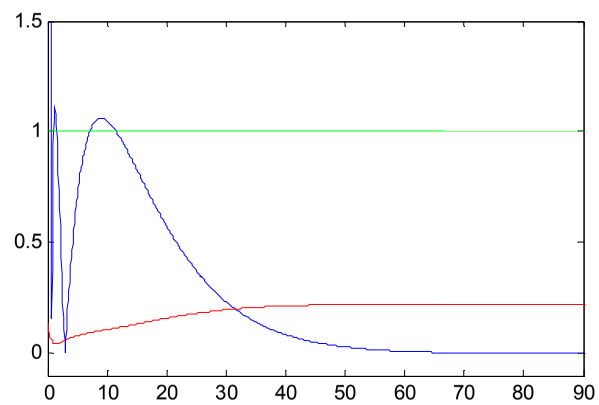
No Fault



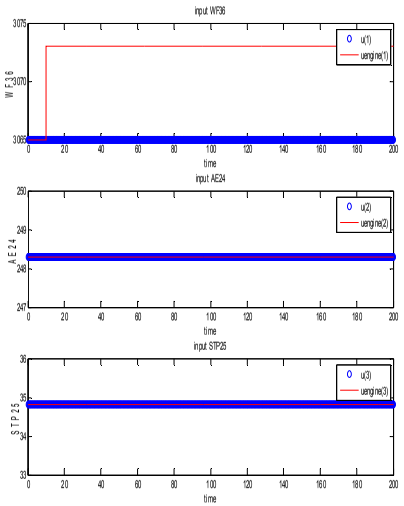

Fault Dectection Using Dynamic Threshold
residual XN2
residual threshold XN2 (z1)
constant threshold

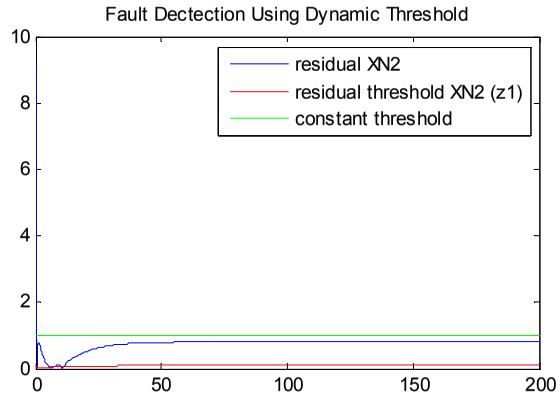

residual XN25
residual threshold XN25 (z2)
constant threshold

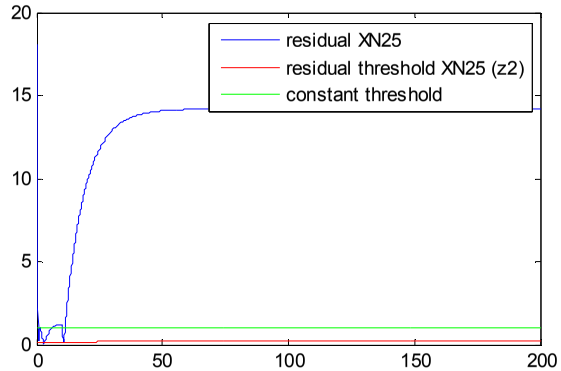


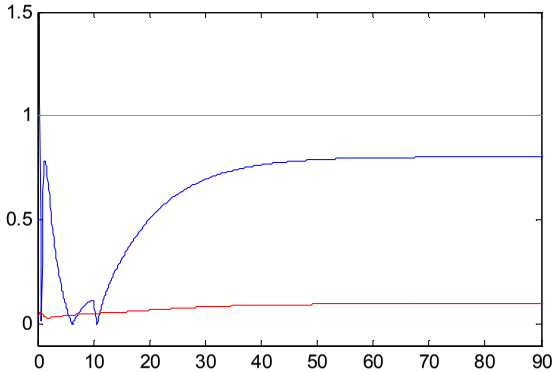


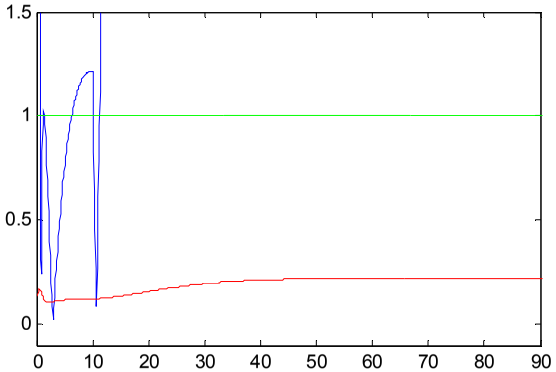
Fault in First Actuator



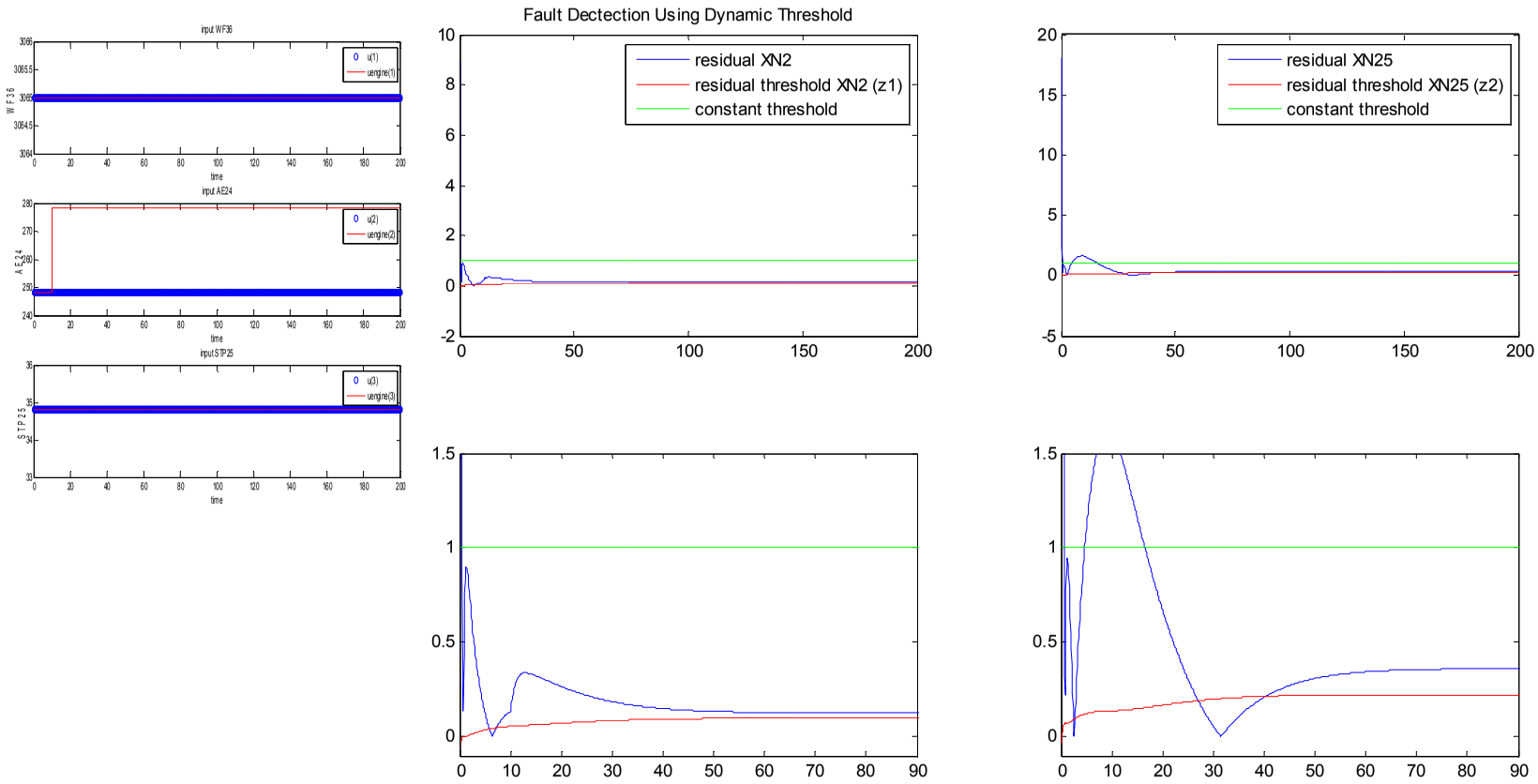




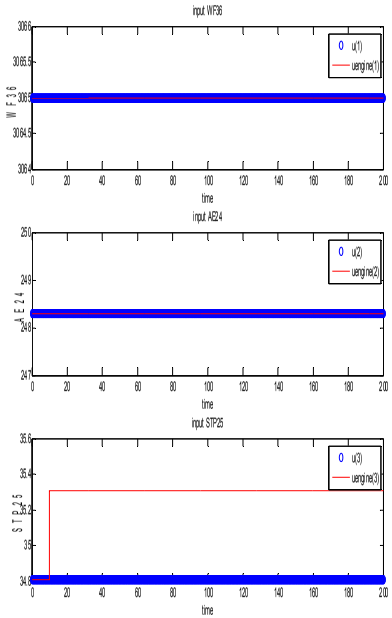


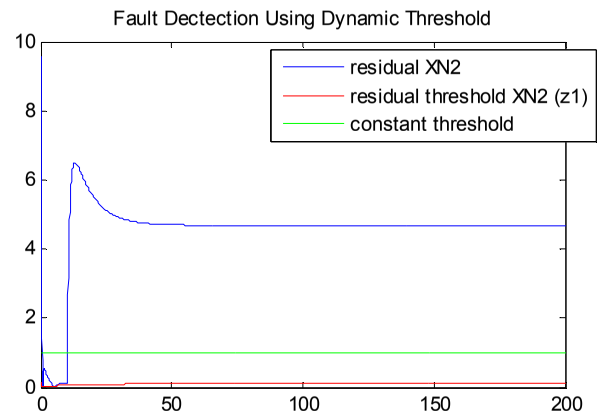


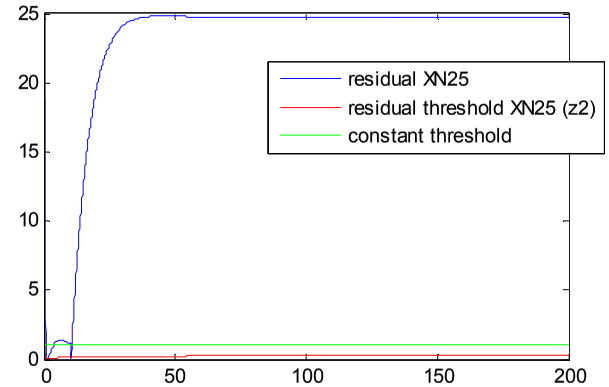
Fault in Second Actuator

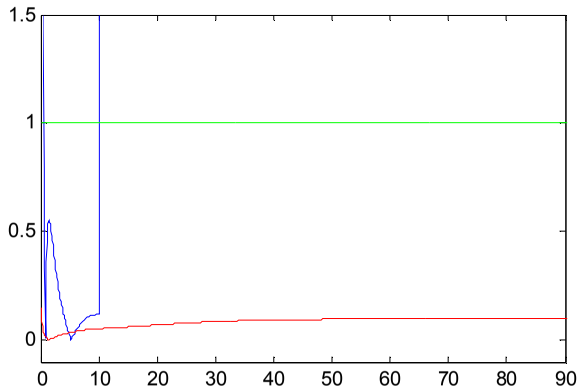


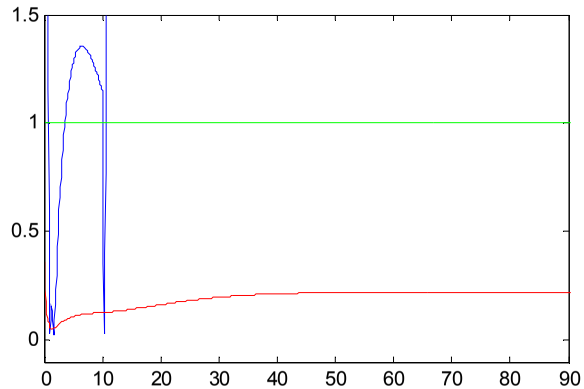
Fault in Third Actuator











Fault Detection Summary

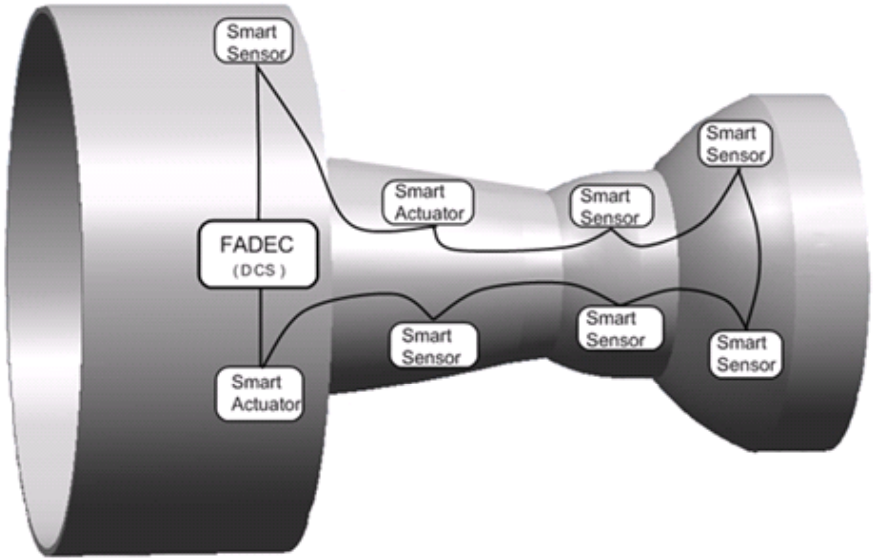
Fault Detection Results

- Dynamic Threshold works well
- First and third actuator faults easier to detect; second actuator fault harder to detect.
- The estimation error in the transient phase relatively large. Better tuning of Kalman filter gain desirable.

Distributed Engine Control System (DEC)

Rohit Belapurkar

- Each sensor/actuator replaced by smart sensor/actuator.
- Signal processing done by smart modules.
- Information transfer through serial communication.
- Smart modules include processing capability to perform health diagnostics and management functions.
- Can be modeled as Networked Control Systems

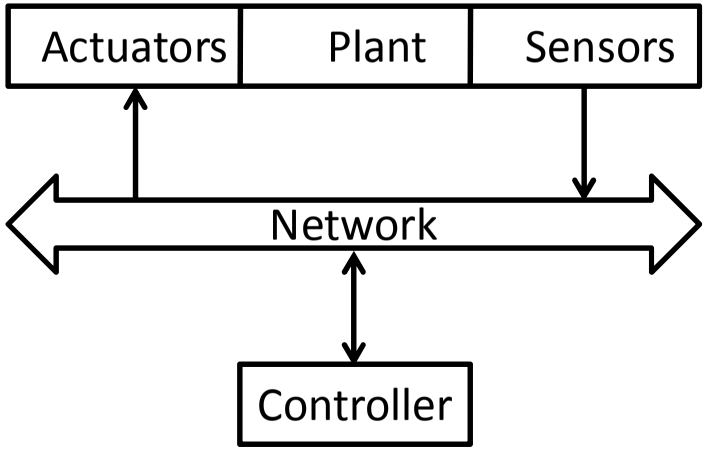


FADEC based on Distributed Architecture

Networked Control Systems (NCS)

Basic elements of NCS

1. Sensors
2. Actuators
3. Communication network
4. Controller

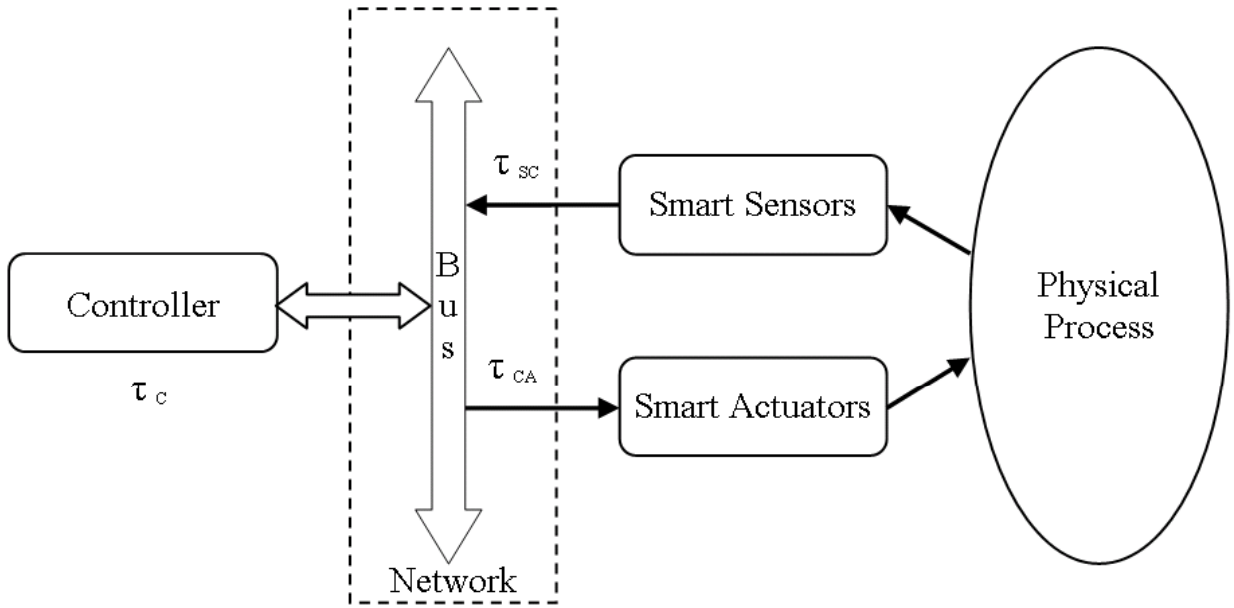


Generic NCS Architecture

Communication Constraints to consider for analysis of NCS

- Packet Dropout
- Network induced Time Delay
- Channel Bandwidth

Time Delay Systems

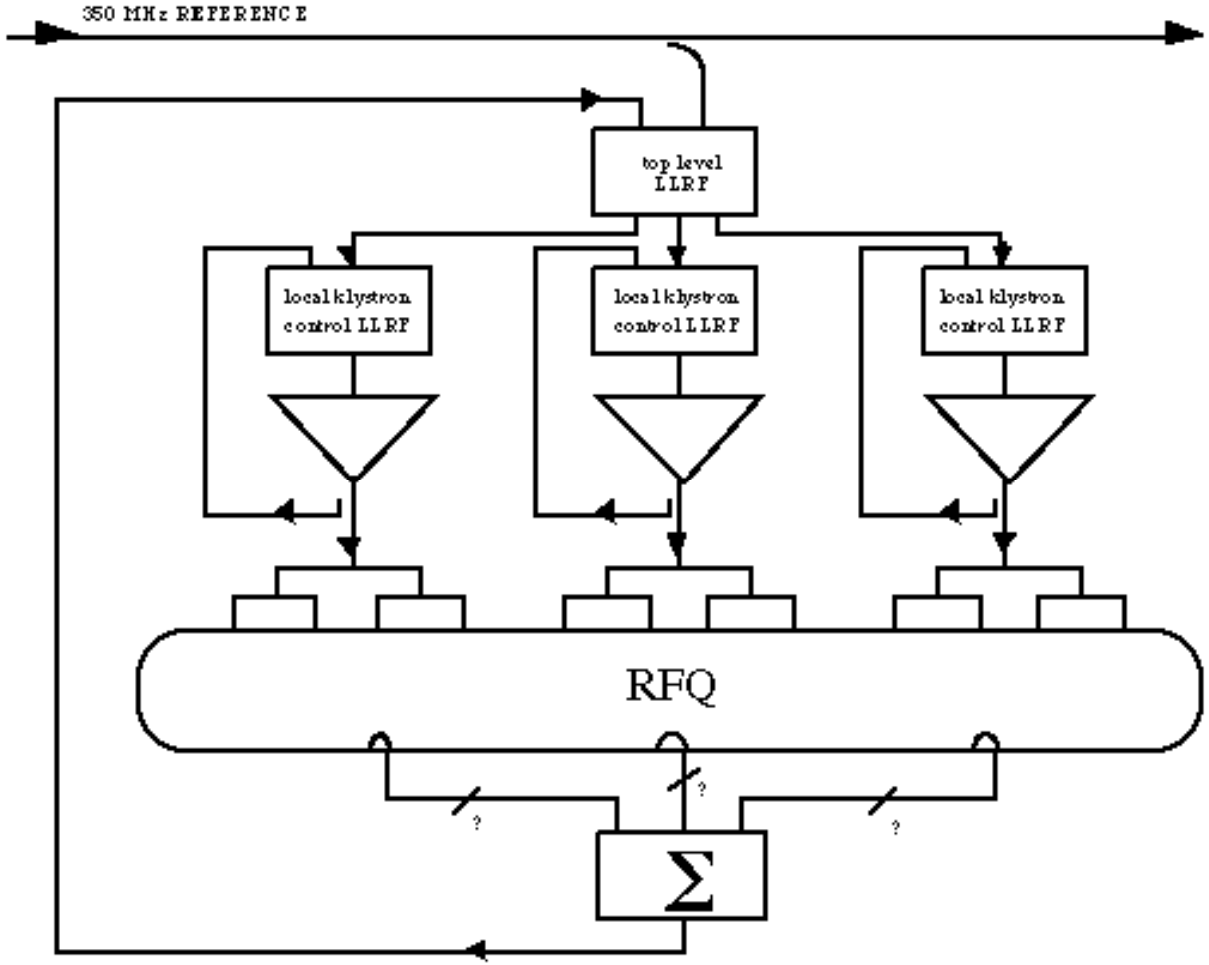


$$\dot{x}(t) = Ax(t) + A_d x(t-\tau) + B_d u(t-\pi)$$

$$x(t_0 + \theta) = \emptyset(\theta), \theta \in [-\tau, 0]$$

$$u(t_0 + \vartheta) = \varphi(\vartheta), \vartheta \in [-\pi, 0]$$

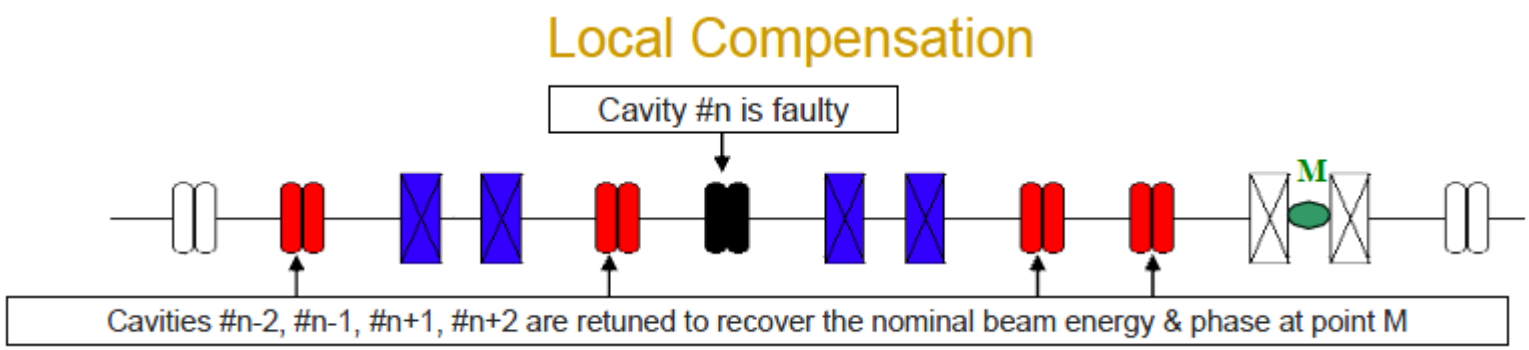
Decentralized Control System for Multiple Klystrons



Block diagram of feedback control system for multiple klystrons

APT LLRF Control System Functionality and architecture- A.H. Regan, A.S. Rohlev, C.D. Ziomek

Fault Tolerant Accelerator



Fault tolerant accelerator demonstrated from beam dynamics point of view

Ref:Enhancing Accelerator Reliability with LLRF Digital Technology-Lucija Lukovac

Proposed OSU Research Topics of Relevance to Fermi-Labs

- LLRF Control Systems: Nominal and Perturbation Modeling and appropriate Robust Control Design

- Fault Detection , Isolation and Accommodation

- Decentralized, Distributed Control with communication constraints/failures taken into consideration

Of course, each of these topics is of immense scope and usefulness and require long term support and collaboration

ROBUST ENGINEERING SYSTEMS, LLC

- Founded in 2008 by Prof. R. K. Yedavalli
- We undertake consulting projects in the related fields of:
  - Robust Control Systems Analysis and Design for Uncertain Dynamic Systems
  - Optimization of Dynamic Systems
  - Distributed Control Systems
  - Control Applications in Various Systems
  - Email: contact@robustengsys.com
  - Website : www.robustengsys.com

Controlling Uncertain Systems With Certainty

Possible Avenues of Collaboration

Very much interested in exploring possible avenues of collaboration with Fermi-Labs

These potentially may include

- PI Research sponsorship for Research to be carried out at OSU with monitoring of progress by Fermi-Labs personnel
- Research Sponsorship can be divided between Robust Engineering Systems and OSU
- Possible Interaction with Other Govt. Labs such as Los Alamos and Oak Ridge
- Exchange of technical information through seminars
- Others?

Summary and Conclusions

- Modern Robust Control Systems Theory has much to offer in the Control of Superconducting Cavity application
- A multidisciplinary team collaboration a necessity for a complex project such as ADS/Project X
- OSU/RES very much interested in contributing to ADS/Project X

- Thank you very much for your attention
- Questions?