Linear Parameter Varying Control and Applications to Active Microgravity Isolation

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Contributions

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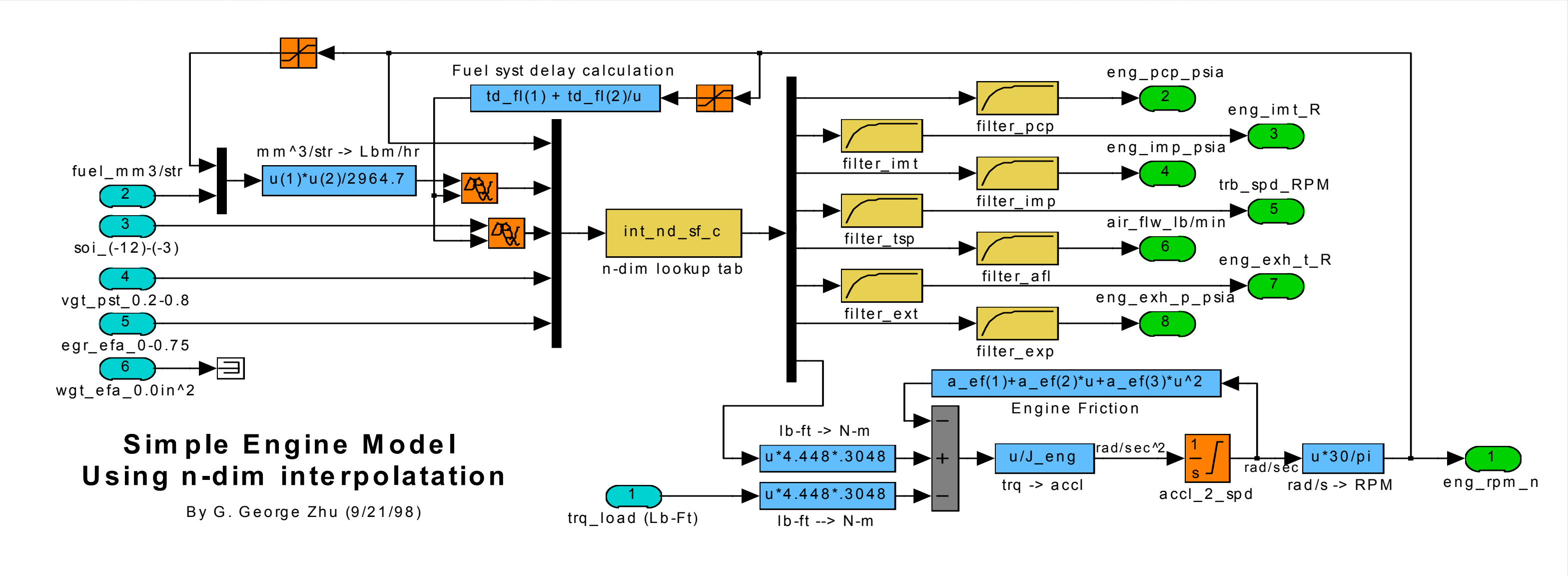
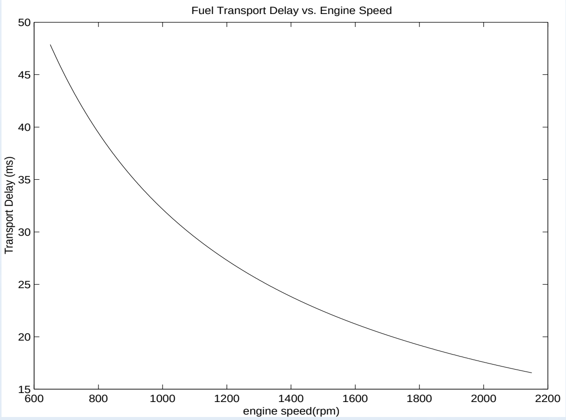
Challenges in the Control of Complex Systems

Complex controlled engineering systems should provide guaranteed reliability and performance in the presence of:

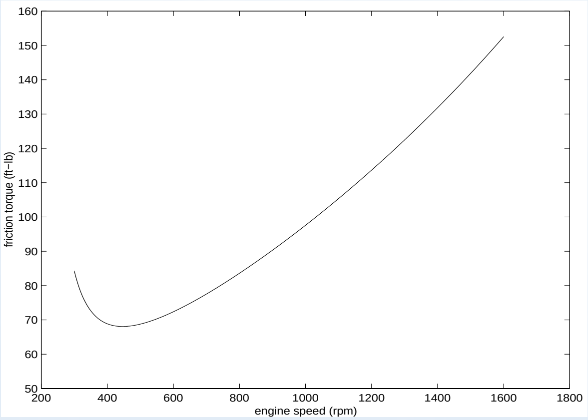
- Variable operating conditions
- System uncertainty and variability
- Changing environment
- System faults
- Actuation limitations
- Time delays
- …

Example: Engine Regulation



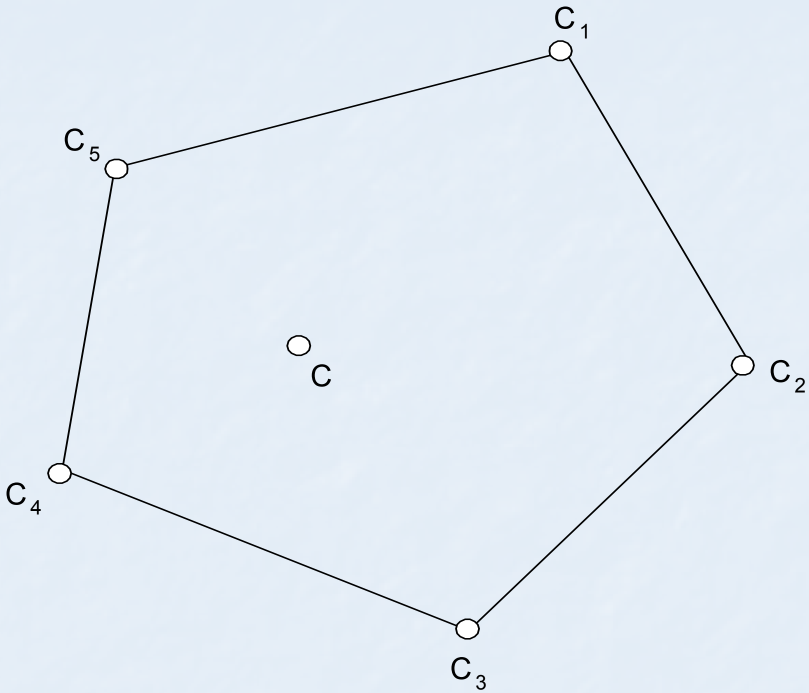


Time delay vs engine speed



Friction torque vs engine speed

Traditional Gain-Scheduled Control



- Divide the operating region into sub-regions
- Obtain linearized models at different operating points
- Use linear control design methods to obtain controllers at each operating point
- Interpolate the controllers to get the full operating envelope control law

Limitations:

- No guaranteed stability or performance
- Inherent restriction to slowly varying operating conditions
- Trajectories restricted to lie close to equilibrium points
- Extensive simulations necessary before implementation
- Long design cycle, difficult implementation

Linear Parameter Varying (LPV) Systems

- System models that depend on variable parameters

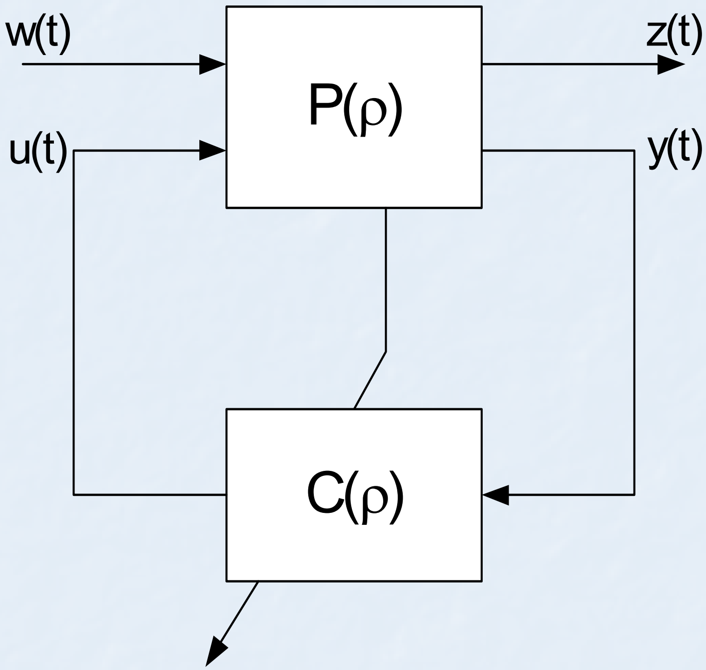
$$
\begin{aligned}
\dot{x}(t) &= A(\rho(t))x(t) + B_1(\rho(t))w(t) + B_2(\rho(t))u(t) \\
z(t) &= C_1(\rho(t))x + D_{11}(\rho(t))w(t) + D_{12}(\rho(t))u(t) \\
y(t) &= C_2(\rho(t))x(t) + D_{21}(\rho(t))w(t)
\end{aligned}
$$

- Set of bounded allowable parameters

$$\underline{\rho_i} \leq \rho_i \leq \overline{\rho_i}$$

- Parameters are measurable in real-time
- Examples:
  1. Aircraft models that depend on Mach number, altitude, dynamic pressure, etc.
  2. Engine models that depend on engine speed, turbocharge pressure, etc.
  3. Robotic systems with variable loads
  4. Nonlinear spacecraft models parameterized with respect to variable operating points

LPV Gain-scheduled Control



- Plant dynamics change depending on time-varying parameter ρ(t)
- ρ(t) not known in advance; measured in real-time.
- Controller is scheduled (adapted) based on measurement of ρ(t)
- Controller *mimics* the nonlinearity of the plant
- No interpolation between families of linear controllers required
- Direct synthesis of nonlinear LPV controller

Advantages of the LPV Gain-scheduled Control

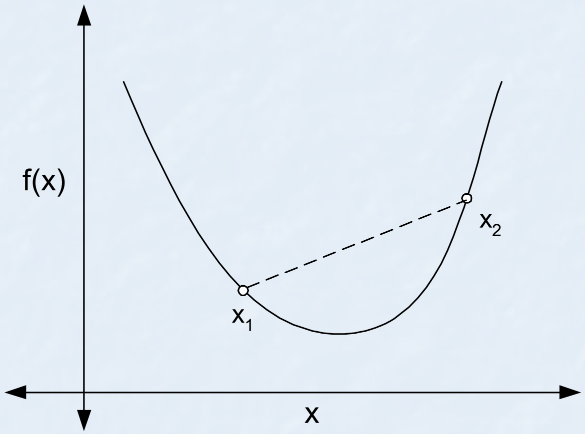
- Useful formulation for systematic gain-scheduling to address system variability

- Guaranteed stability and performance

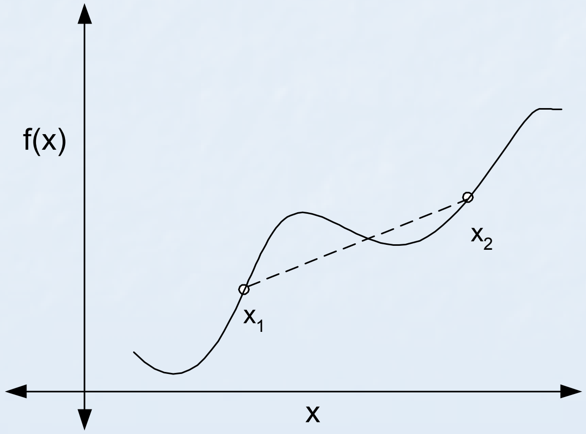
- Utilizes optimization-based performance measures (for example, extensions of linear optimal H_∞ design methods)

- Synthesis conditions in terms of Linear Matrix Inequalities (LMIs); a convex optimization problem

Convex Functions



Convex function



Non-convex function

- Function f is convex if for any two points x_1 and x_2 the graph of f lies on or below the line joining (x_1,$f(x_1)$) and (x_2,$f(x_2)$).
- Linear (and affine) functions are convex.
- Convex functions are easy to minimize. ☺

Linear Matrix Inequalities (LMIs)

- Matrix Inequality constraints of the form:

$$F(x) = F_0 + x_1 F_1 + \ldots + x_m F_m > 0$$

  - $x = (x_1, \ldots, x_m)$ is the vector of decision variables.
  - $F_1, \ldots, F_m$ are real symmetric matrices.
  - $F(x) > 0 \equiv$ smallest eigenvalue of $F(x)$ is positive.

- The LMI $F(x) > 0$ defines a convex constraint on x.

- Minimization of a convex functional f subject to the LMI constraint $F(x) > 0$ is a convex optimization problem.

- Efficient numerical algorithms exist to solve the above problem.

Example: Linear System Stability

- **Stability**

  Matrix A is stable if: $AX + XA^T < 0$ where $X > 0$

- **Multi-system stability**

  Matrices A_1, A_2, A_3 are stable if:

$$A_1 X + X A_1^T < 0$$

$$A_2 X + X A_2^T < 0$$

$$A_3 X + X A_3^T < 0$$

where $X > 0$.

*LMI Control Toolbox**

- Provides efficient computational solution of LMI problems

- Provides ready-to-use tools for LMI-based control systems analysis and design
  - Robustness analysis for uncertain systems
  - Multi-objective feedback control synthesis (optimal disturbance rejection, pole placement, gain minimization)
  - Loop shaping design
  - Robust gain scheduled control

* P. Gahinet at al, *LMI Control Toolbox For Use with MATLAB*, The MathWorks, 1995.

Example: LPV Stability Analysis

$$\dot{x} = A(\rho)x$$

where

$$\begin{aligned} A(\rho) &= \alpha_1 A_1 + \ldots \alpha_n A_n \\ \alpha_i &\geq 0, i = 1, \ldots, n, \sum_{i=1}^{n} \alpha_i = 1 \end{aligned}$$

- The plant dynamics are given by a convex combination of vertex systems

Example: LPV Stability Analysis

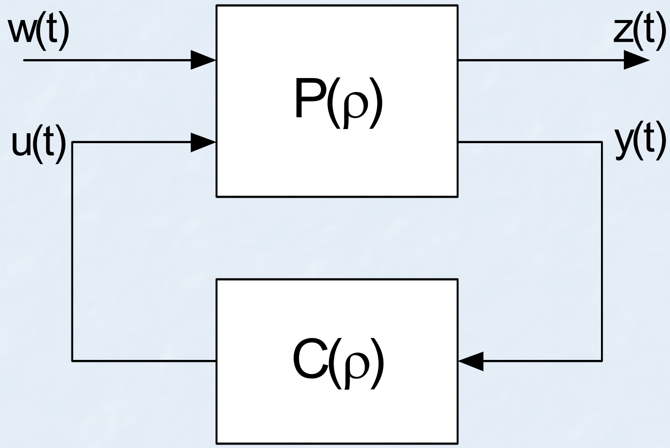
The LPV system is stable if the LMI

$$\begin{aligned} P &> 0 \\ A_i^T P + P A_i &< 0, i = 1, \ldots, n \end{aligned}$$

in the unknown variable P is feasible

- If the above LMI problem is feasible, stability is guaranteed for all parameter variations
- The parameter variations can be arbitrarily fast

Disturbance Rejection



- **Problem**: Design feedback controller *C* to minimize the effect of the disturbance w(t) on output z(t)
- Other performance specifications:
  - Good transient response
  - Small steady state error

System Gains

- Norm based performance: Disturbance rejection as gain minimization

  - Energy-to-energy gain (H_∞) minimization

$$\min_{C} \sup_{w \in L_2 - \{0\}} \frac{\|z\|_2}{\|w\|_2}$$

  - Energy-to-peak gain minimization

$$\min_{C} \sup_{w \in L_2 - \{0\}} \frac{\|z\|_\infty}{\|w\|_2}$$

Example: Disturbance Rejection

- General LPV controller $\mathcal{C}(\rho)$

$$\begin{aligned} \dot{x}_k(t) &= A_k(\rho(t))x(t) + B_k(\rho(t))y(t) \\ u(t) &= C_k(\rho(t))x(t) + D_k(\rho(t))y(t) \end{aligned}$$

- Computation of $\mathcal{C}(\rho)$ requires solution of family of LMIs

- The controller is scheduled on the parameter and its rate of variation

- Stability and performance is guaranteed for all operating points and all parameter variations

- Numerical computation of $\mathcal{C}(\rho)$ is a convex optimization problem

LPV for Microgravity Isolation

- Design microgravity isolation controllers that are adapted from a "soft" setting to a "stiff" setting to avoid hitting the hard-stops
- Adapt the microgravity isolation controllers to the harshness of the operating environment
- Adapt the microgravity isolation controllers to the saturation level of the actuators

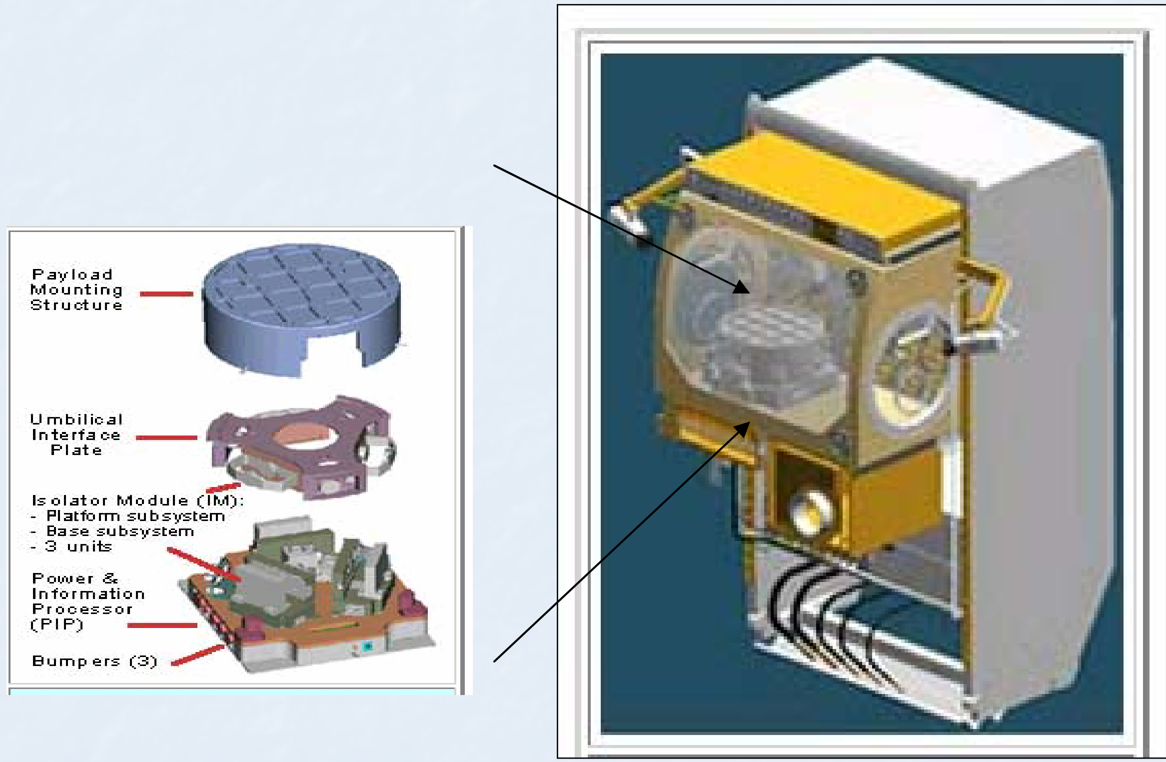
The Microgravity Isolation Problem
Motivation

- The ISS is a premier laboratory to conduct acceleration sensitive microgravity experiments.
- There exist variety of vibro-acoustic disturbances abroad the station
  - Low frequency excitations (< 0.001 Hz). Due to gravity gradient forces and atmospheric drag.
  - Intermediate range vibrations (0.001 to 1 Hz). Transient in nature; Occur due to astronaut motion, thruster firing etc.
  - High frequency vibrations (> 1Hz). Caused by steady state sources like pumps, fans, compressors and transients sources such as impacts.
- It is required to maintain a strict microgravity environment and attenuate vibro-acoustic disturbances .

The Microgravity Isolation Problem

Isolation Platform Examples: Payload Level

Microgravity Isolation Mount [MIM]



Glovebox Integrated Microgravity Isolation Technology [g-LIMIT]

The Microgravity Isolation Problem

Isolation Platform Examples: Rack Level

1 Dual Processor : Decoupling implemented in controller allows freedom to place actuators and sensors. Payloads have extensive command, data acquisition, and control options.

2 3 Sensor Electronic Units : Programmable analog filters & gains & 16 bit analog-to-digital converters.

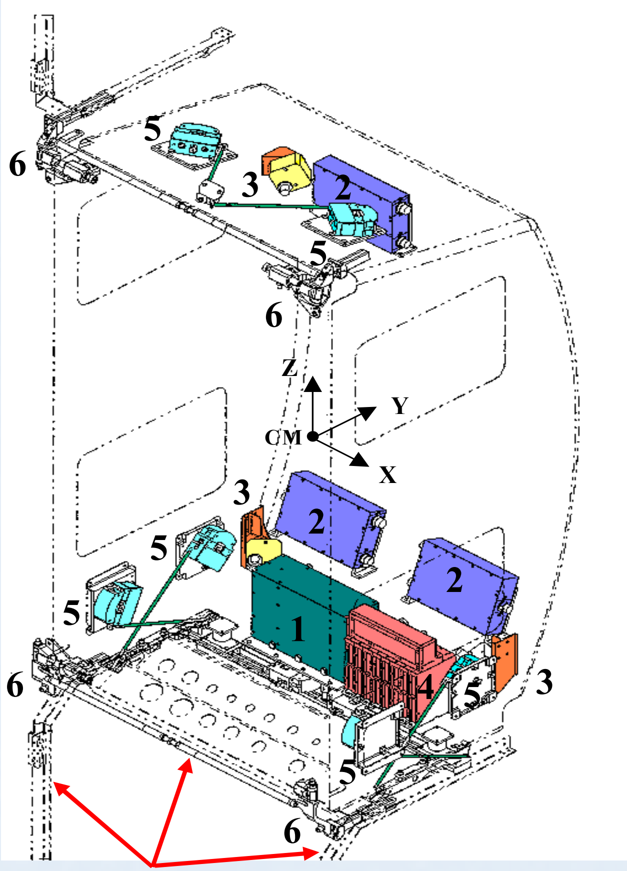
3 Accelerometer Heads : Built small to fit in rack corners. 3 Tri-axial heads.

4 8 Actuator Drivers : Pulse width modulation used to reduce power consumption

5 8 Actuators : Voice coil rotary actuator used to reduce profile and power consumption.

5 8 Position Sensors : Integrated with actuators.

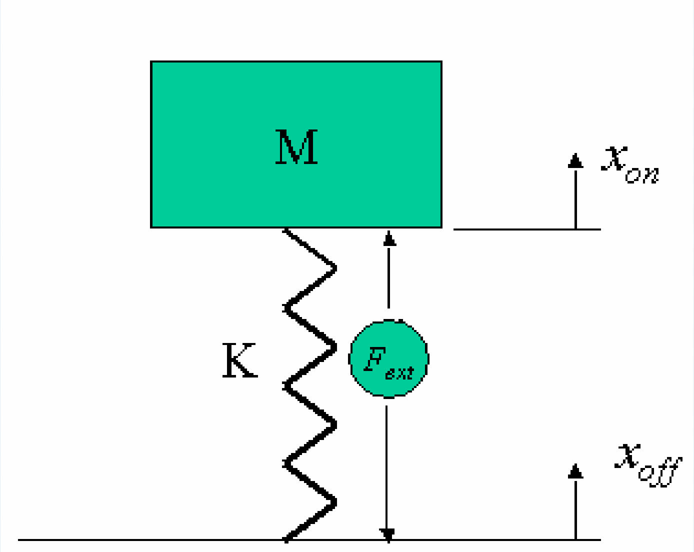
6 Hard stop Bumpers



STATION STANDOFF STRUCTURE

Active Rack Isolation System [ARIS]

The Microgravity Isolation Problem
Modeling



Equation of Motion

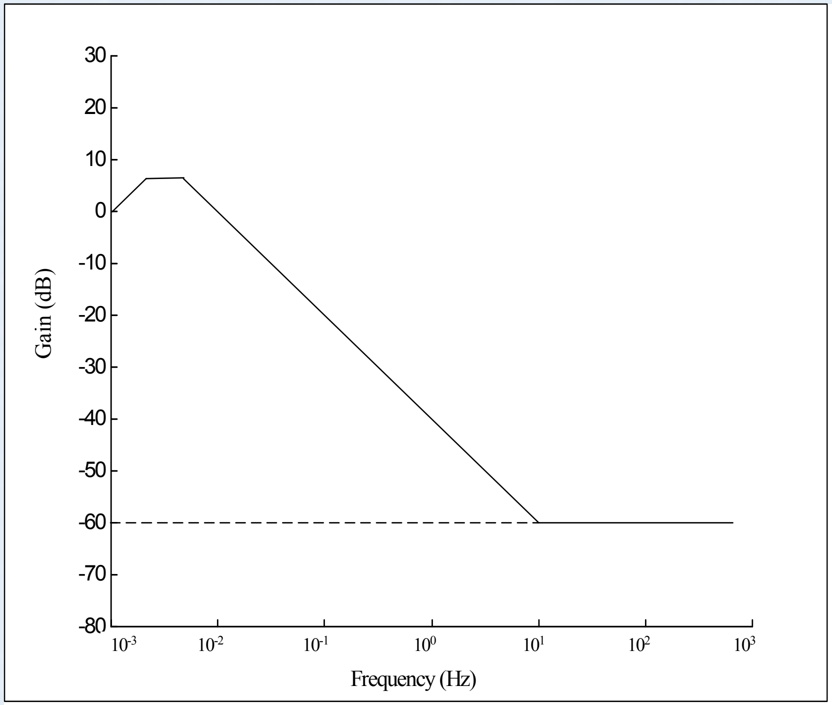
$$M\ddot{x}_{on} + K[x_{on} - x_{off}] = F_{ext}$$

- Kinematic and dynamic decoupling reduces the problem to 6 independent DOF.
- Rigid body model. Flexible modes neglected.
- M: Mass of isolated platform.
- K: Stiffness element modeling coiled umbilicals.
- F_{ext}: Control force applied between the isolated platform and base.
- x_{on}, x_{off}: Onboard and Off-board displacements.

The Microgravity Isolation Problem
Design Objectives

- Attenuate vibro-acoustic disturbances to maintain a microgravity environment. Level of isolation defined as ratio of onboard to off-board acceleration.

- Restrict relative motion within a specified rattlespace enforced by hardstops.

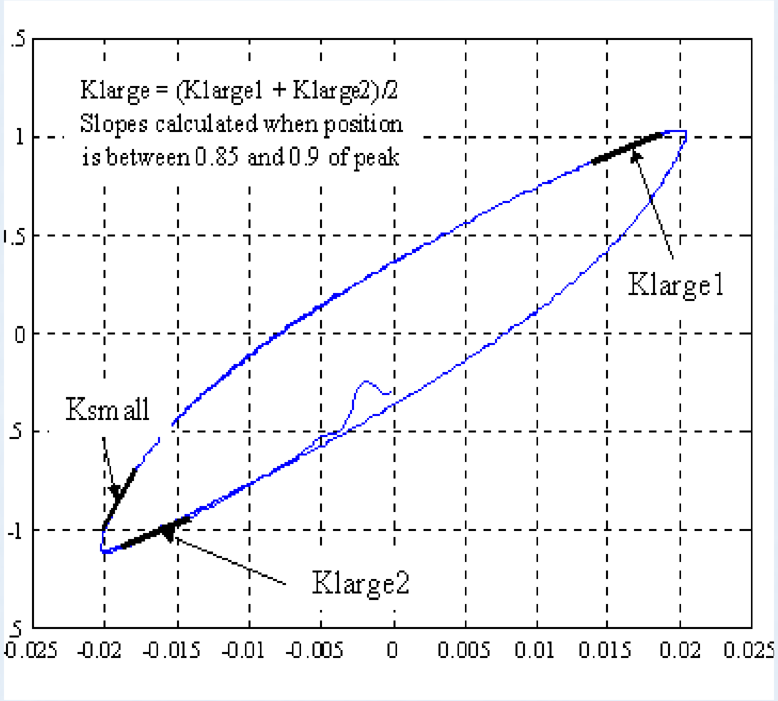


Typical target isolation curve

The Microgravity Isolation Problem

Design constraints

- Spring constant K varies hysteretically over the range of displacement. Variation assumed to lie in the interval [0,30] lbf/ft.
- Neglecting flexible modes introduces a structural dynamic uncertainty at high frequencies.
- Accelerometer noise: Occurs at low frequencies.
- Position sensor noise: Occurs at high frequencies.



Displacement vs. Spring Force

Adaptive Active Isolator

Design Goal

Achieve good vibration isolation performance over the range of displacements without bumping into the hardstops.

Past Approaches

- Linear controllers that focus only on isolation performance risk bumping in the presence of transient disturbances.

- Most microgravity platforms implement some sort of nonlinear outer loop controller that activates when bumping is imminent.

Adaptive Active Isolator

Proposed 2-level adaptive isolation

We propose a novel 2-level adaptive isolation strategy based on the variability of the rack displacement and the operating environment.

I. ***Adaptation to rack displacement (1st level of adaptation)***

- Focus on good isolation performance when displacement small (soft setting).
- Focus on minimizing displacement when rattlespace limits are approached (stiff setting).
- Change focus from isolation performance to displacement minimization and vice versa as the displacement changes.

❖ *Performance is parameterized by ρ_d a continuous nonnegative function of displacement.*

Adaptive Active Isolator

Proposed 2-level adaptive isolation

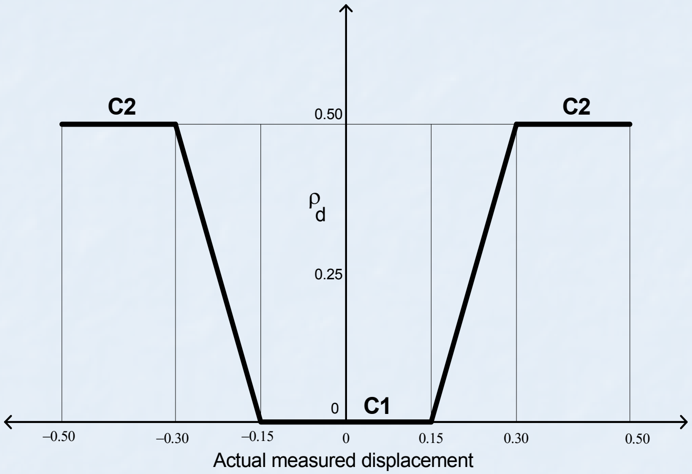
II. ***Adaptation to Operating Environment (2nd level of adaptation)***

- Operating environment quantified using parameter $\rho_r \in [0,1]$
- Smooth environment (minimal disturbances) $\leftrightarrow \rho_r = 0$
- Rough environment (significant station disturbances) $\leftrightarrow \rho_r = 1$
- In smooth operating conditions (small values of ρ_r): Focus on good isolation for a wide range of displacements rapidly shifting focus to displacement minimization as limits are approached.
- In rough operating conditions (large values of ρ_r): Continuously shift focus from isolation performance to displacement minimization so that bumping is avoided.

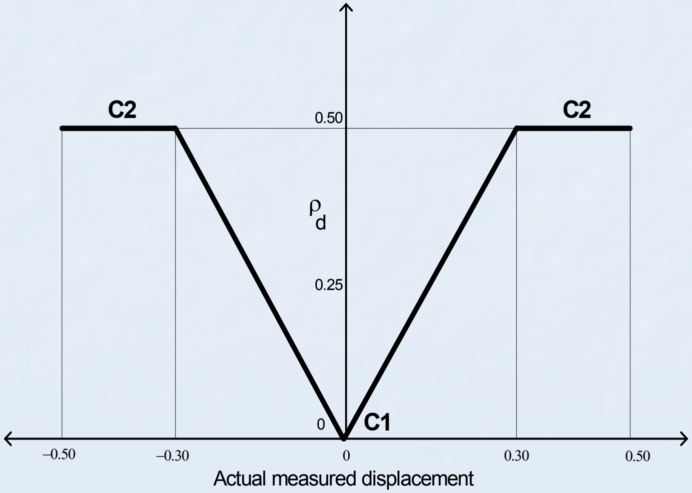
Adaptive Active Isolator

Adaptive scheduling strategies

- C1 and C2 denote the adaptive isolator in its softest and stiffest settings respectively.
- Strategy *S1* corresponds to $\rho_r = 0$ (Smooth operating environment strategy).
- Strategy *S2* corresponds to $\rho_r = 1$ (Rough operating environment strategy).
- A continuous change from *S1* to *S2* is carried out depending on the current value of ρ_r.



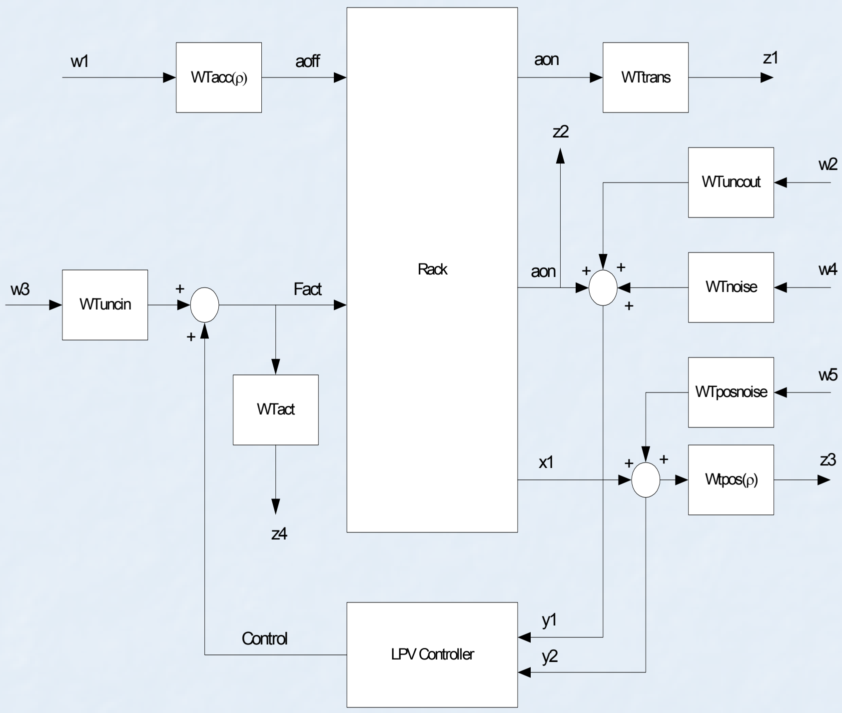
Scheduling strategy *S1*



Scheduling strategy *S2*

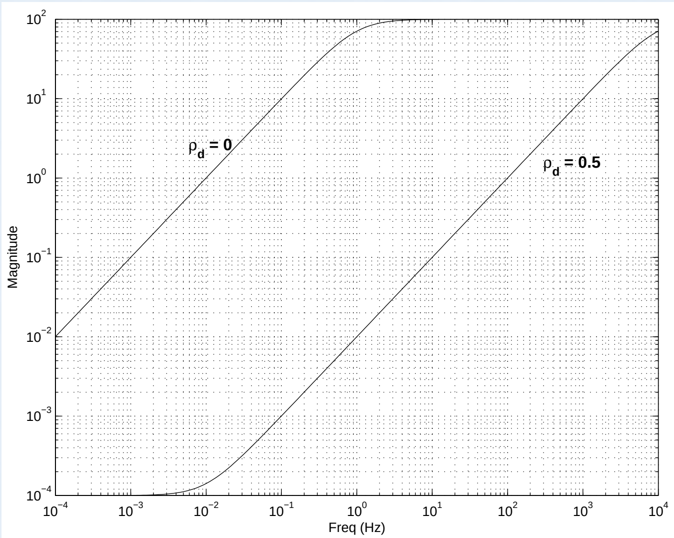
Adaptive Active Isolator
Problem formulation and solution

- Performance requirement specified in terms of induced L_2 norms using parameter-dependent weighting functions.
- Parameter-dependent weights reflect adaptive performance specifications.
- Design problem formulated as a Linear Parameter-Varying (LPV) control problem.

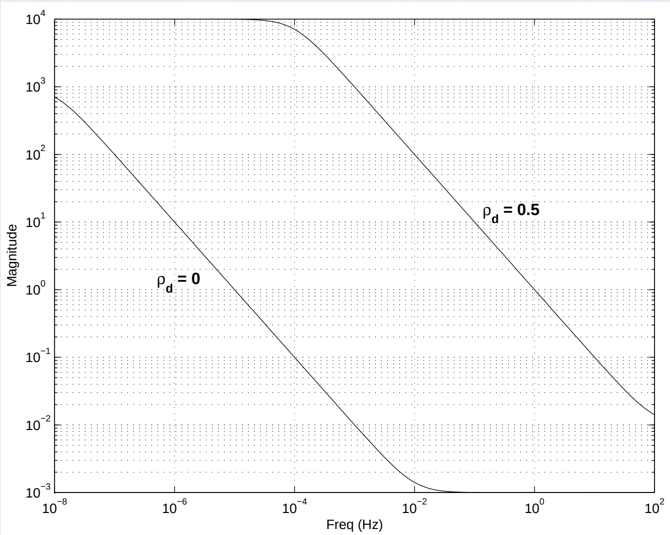


Control design interconnection

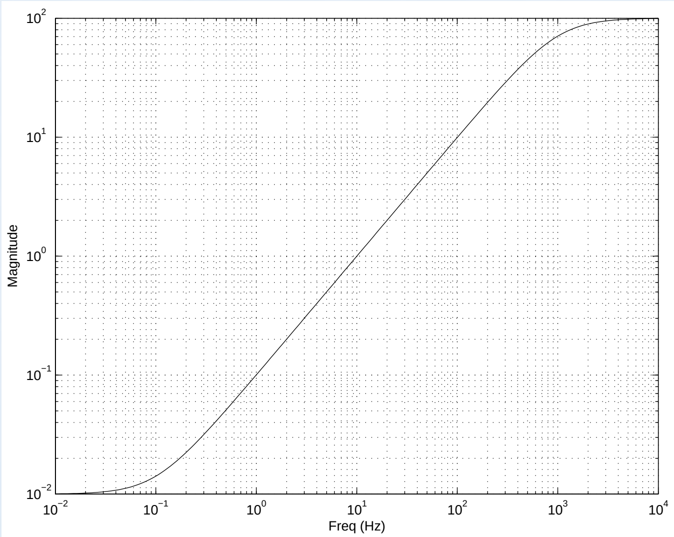
Adaptive Active Isolator
Problem formulation and solution



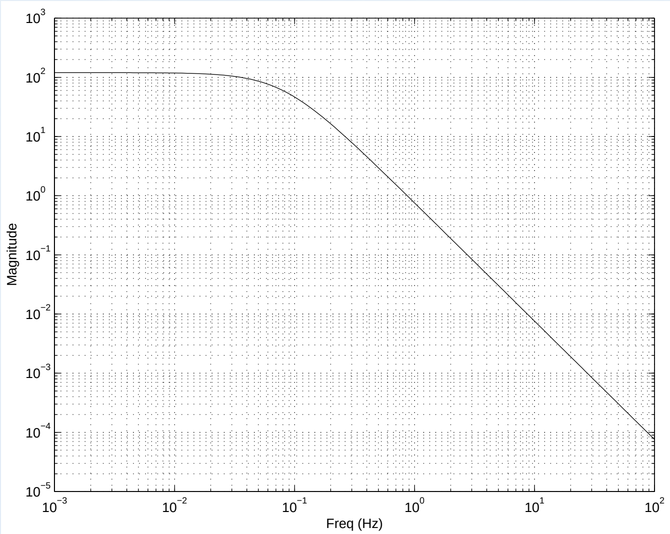
Offboard Acc



Position



Out Uncert



In Uncert

Adaptive Active Isolator

Problem formulation and solution

- The LPV controller is a function of the parameters ρ_d and ρ_r and adapts its performance in real time based on the current values of these parameters.

$$C_{LPV} = C_K(\rho)\,(sI-A_K(\rho))^{-1}B_K(\rho)+D_K(\rho), \text{ where } \rho=(\rho_d,\rho_r)$$

- Maximum rate of change of ρ_d is assumed to be $\pm$ 0.025 and ρ_r is assumed to be a slowly changing parameter.

- Solution obtained by solving a set of 3 parameter-dependent linear matrix inequalities (LMIs).

Adaptive Active Isolator
Problem formulation and solution

- The above problem is converted to a finite dimensional LMI optimization problem by
  - Gridding the parameter space
  - Choosing basis functions that define the functional dependence of the Lyapunov matrices on the parameters.
- The solutions obtained are validated on a dense grid in the parameter space.
- The LPV controller has order 9.
- The LPV controller is also a function of the rates of change of the parameters ρ_d and ρ_r.

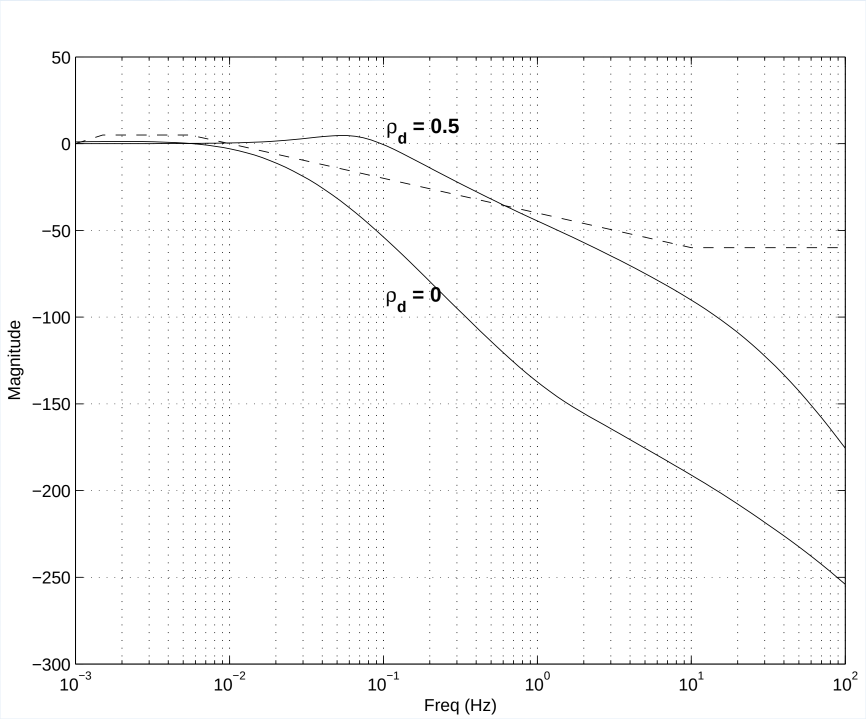
Presentation of results
Frequency domain analysis

- Isolation curve for soft setting rolls off around 0.015 Hz.

- ρ_d = 0 (Rack centered in sway space). Performance based design meets requirement of good isolation.

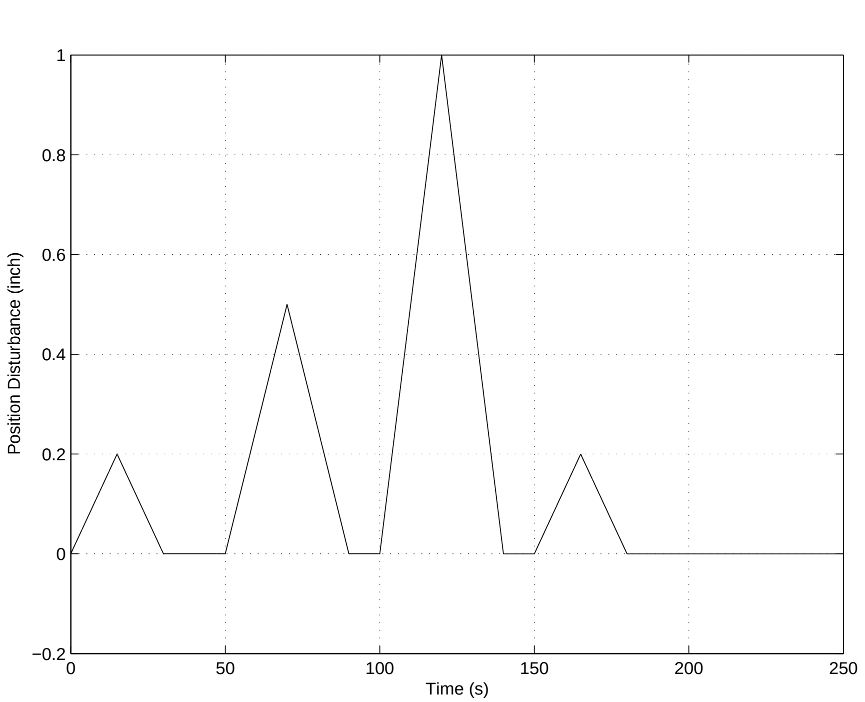
- Isolation curve for the stiff setting rolls at 0.1 Hz resulting in better position control.

- ρ_d = 0.5 (Rack near hardstops) leads to a design which tries to avoid bumping.



Presentation of results
Time domain simulations

- Time domain simulations carried out with the position disturbance signal applied under *S1, S2* and an adaptive switching rule.

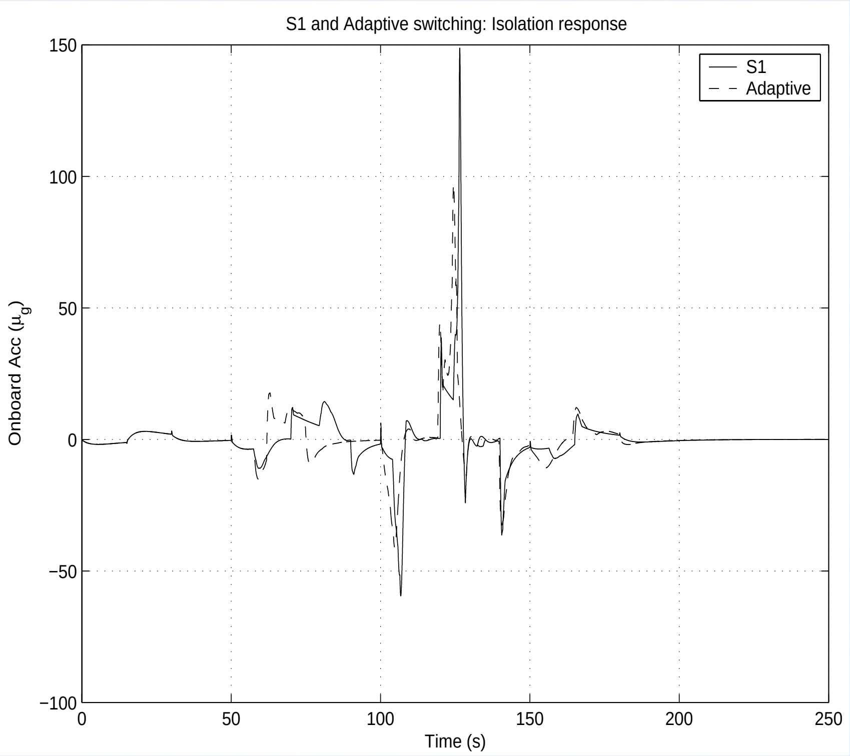


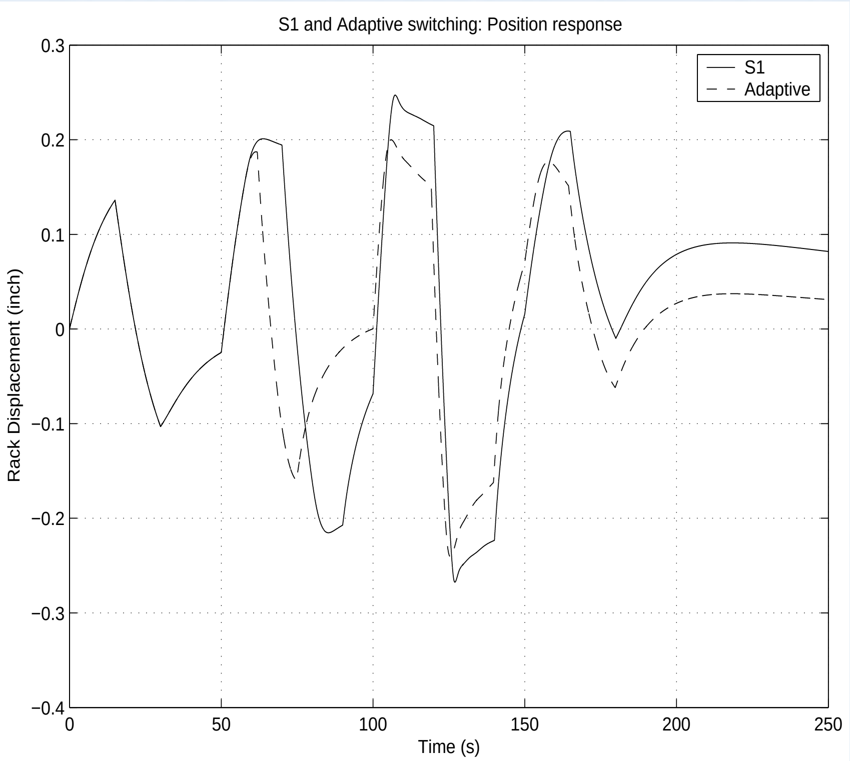
Adaptive switching rule

- Start operation in *S1.*
- If displacement is greater than 0.15 inches smoothly switch to *S2*.
- If displacement remains below 0.15 inches for 100 sec switch back to *S1*.

Time domain simulations

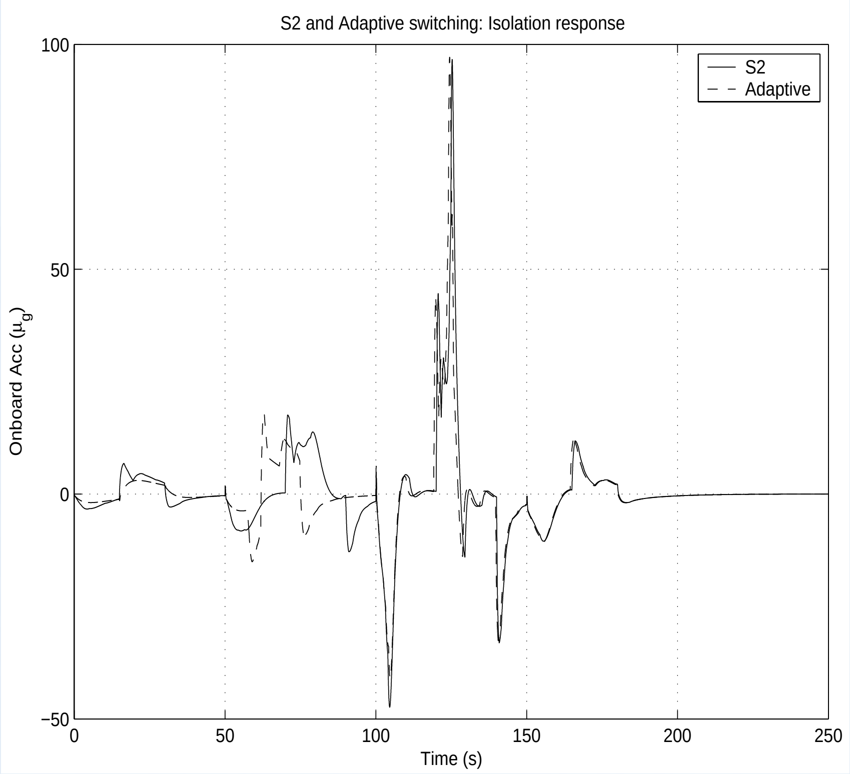
S1 and adaptive isolation strategy

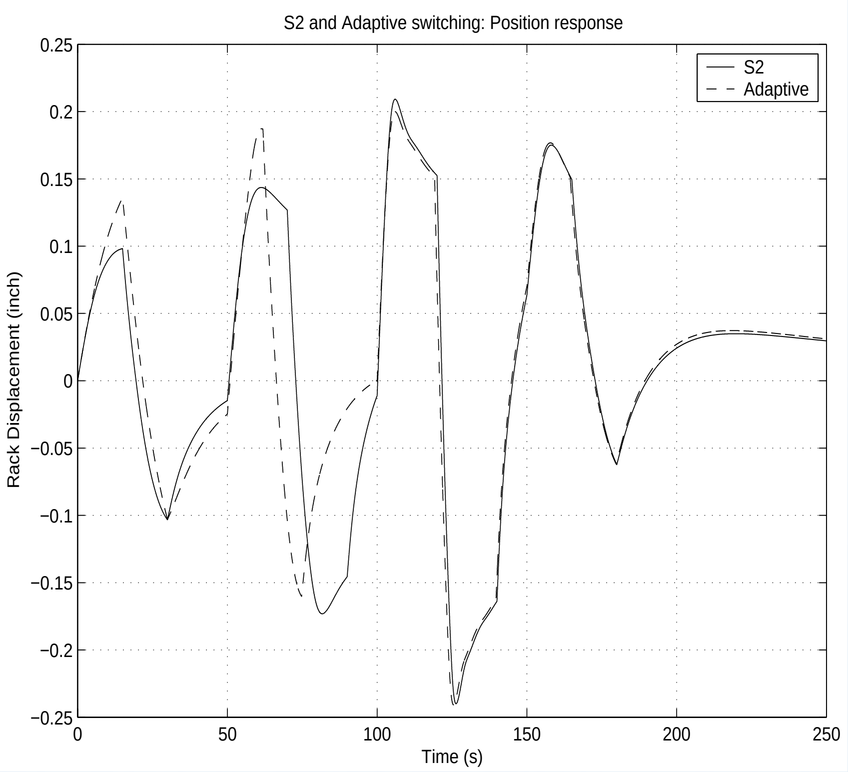




Time domain simulations

S2 and adaptive isolation strategy





Time domain simulations

- *S1* provides better isolation response for small disturbances (smooth environment) than *S2,* where as *S2* provides better isolation over large inputs due to gradual stiffening.
- Both *S1* and *S2* appropriately restrict displacement.
- Adaptive switching strategy provides optimal performance over the whole range of inputs by operating as *S1* for smooth operating conditions switching to *S2* over the first 0.8 inch input. Switch back to *S1* occurs once the displacement has been kept below 0.15 inches for 100 seconds.

Observations

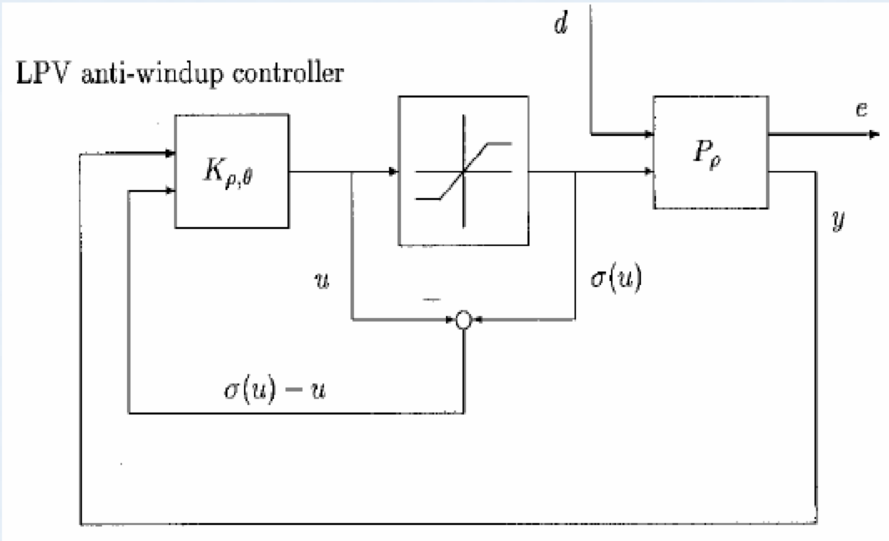
- Design of an adaptive LPV controller with parameter-dependent performance is carried out for microgravity isolation.

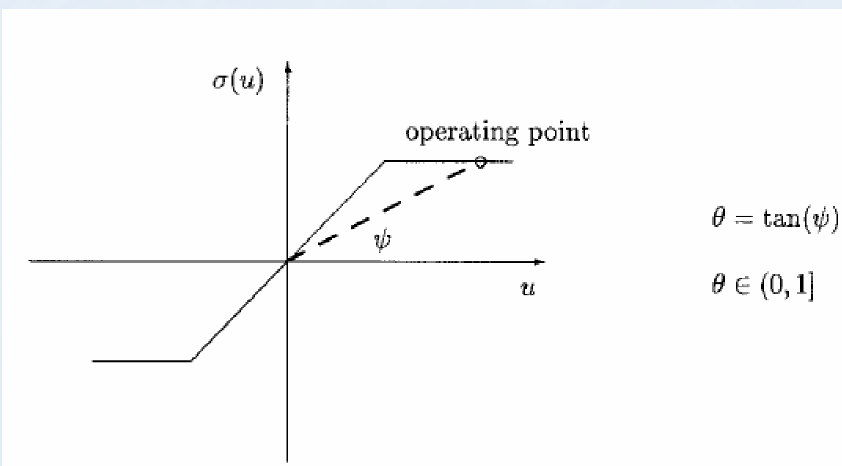
- The LPV controller is scheduled on two parameters ρ_d and ρ_r, or in other words, on displacement and harshness of operating environment.

- This strategy provides good isolation and prevents bumping into hardstops.

- Nonlinear simulations show the merit of the adaptive approach.

Extensions: Anti-Windup LPV (AWLPV) Control





Define saturation indicator parameters

$$\theta_i(u_i) = \frac{\sigma(u_i)}{u_i}, \quad \text{for } i = 1,2,\dots,n_u$$

Design LPV controllers that are scheduled (adapted) with respect to both ρ and θ

$$u = K(\rho,\theta)$$

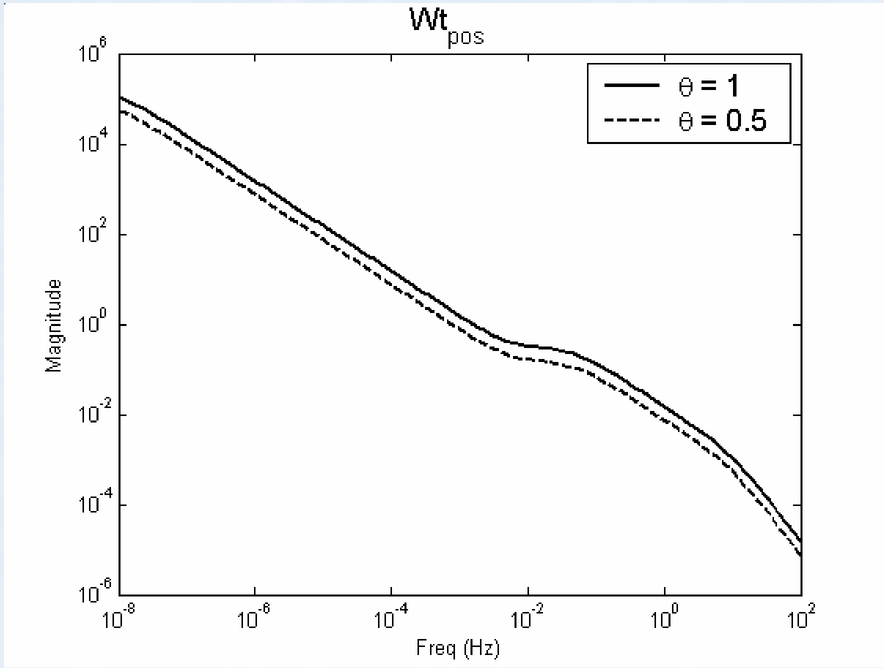
to guarantee:

- Stability
- performance
- Disturbance rejection

Application to Microgravity Isolation

System parameters

- Mass of the rack: 15 slugs
- Spring constant k lies between 0 and 20 lb/ft.
- Actuator saturates at 3 lb.



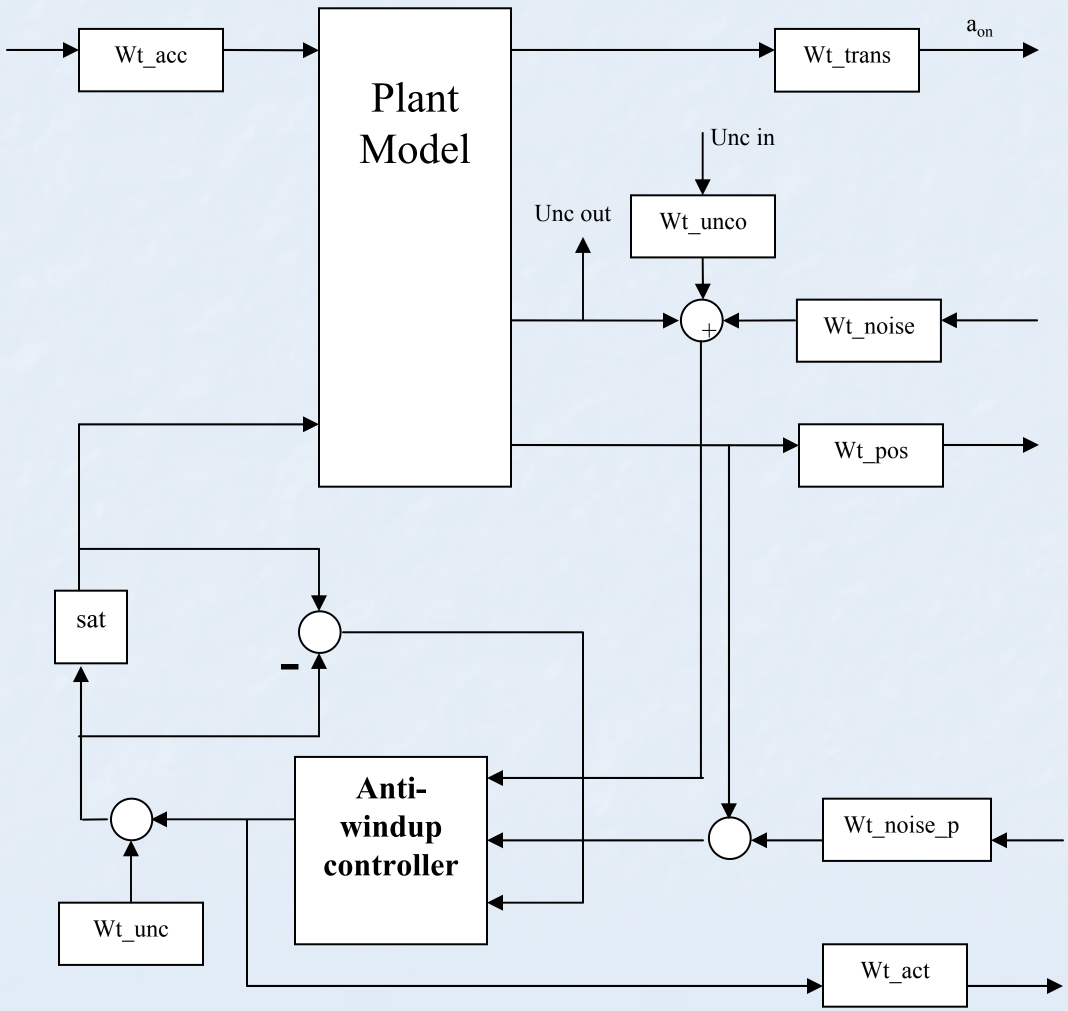
Parameter dependent weight

$$w_{act}(\theta) = 10^{-5} + 3 * 10^{-4}(1-\theta)$$

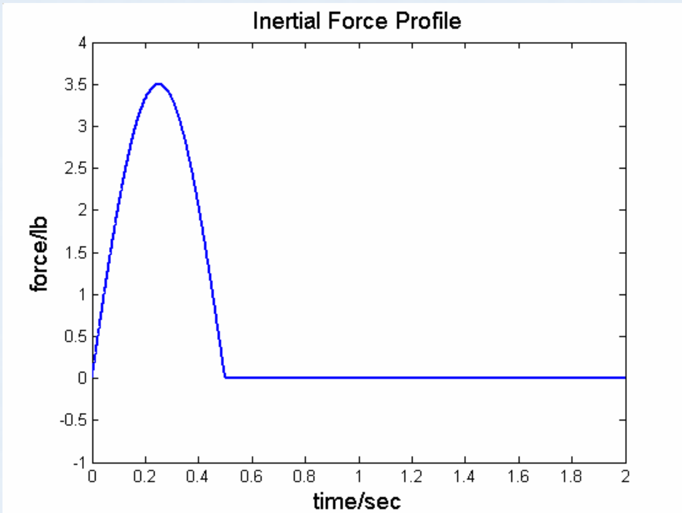
$$w_{trans}(\theta) = 10^{-5} + (1-\theta) * 1.8$$

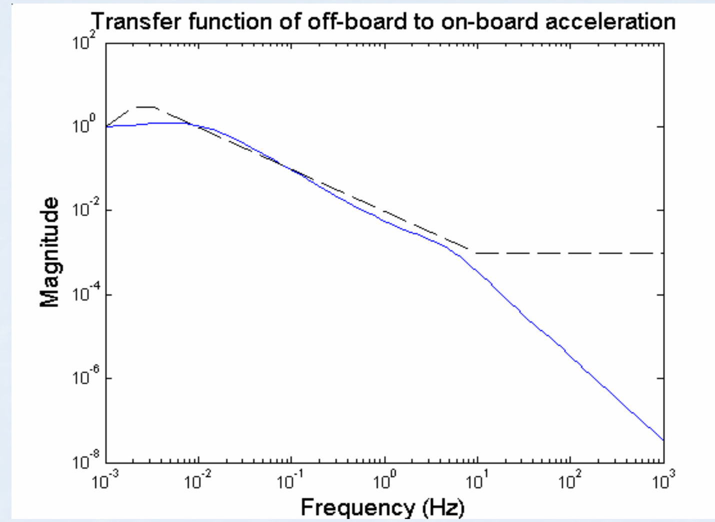
$$\theta \in [0.5, 1]$$

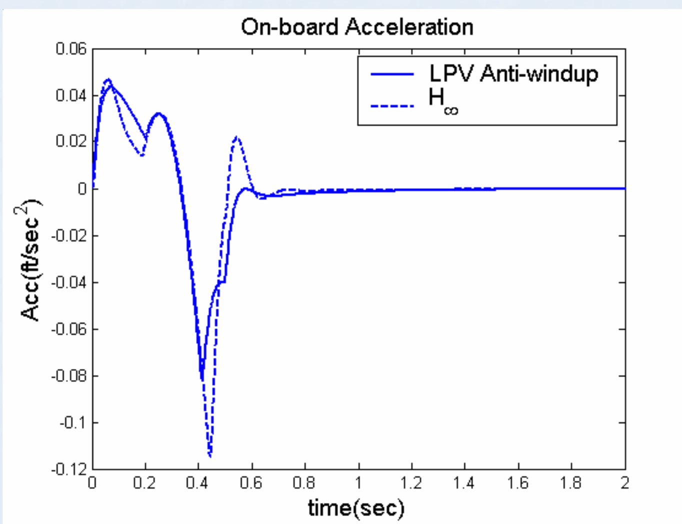
Weighted Closed-Loop Interconnection

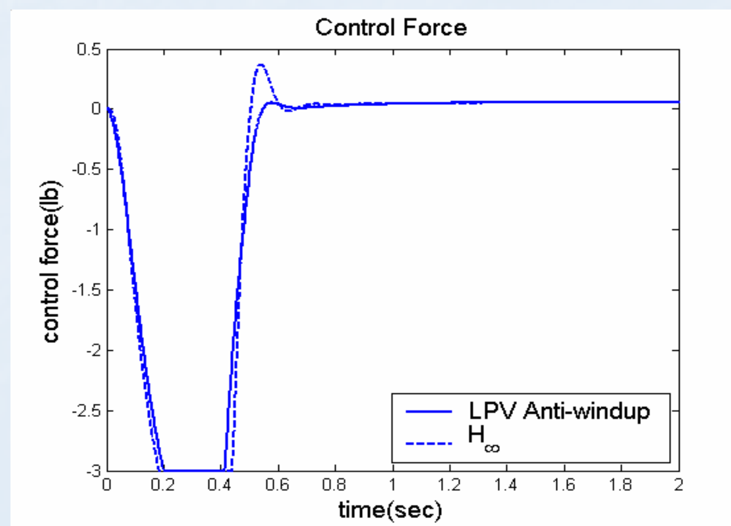


Design Results and Controller Validation

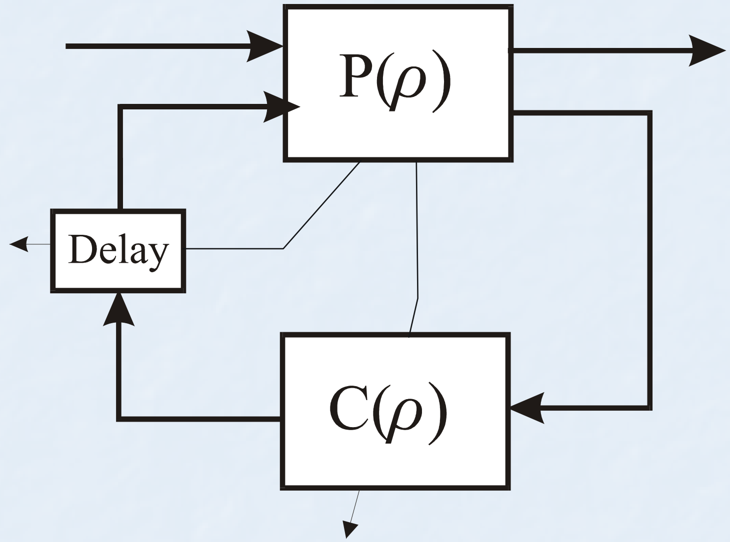








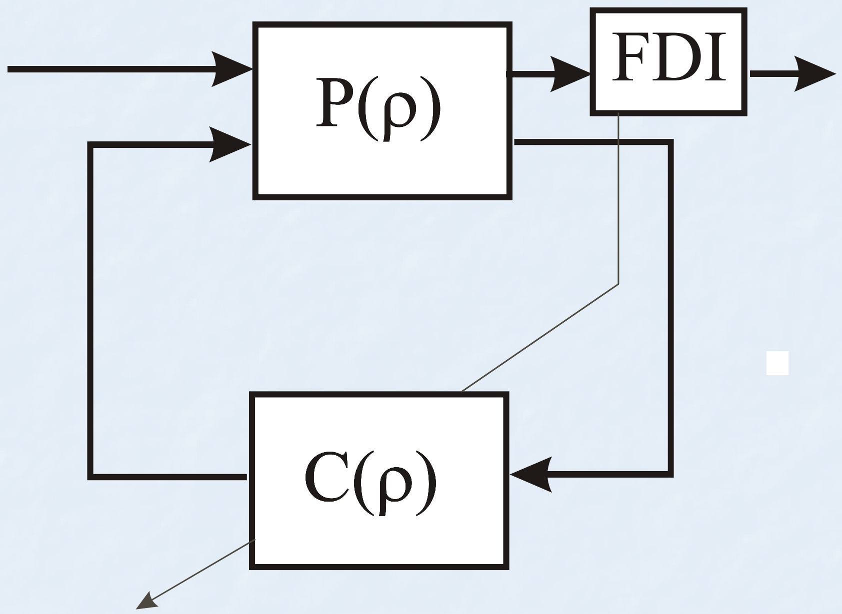
Extensions: Control of Systems with Variable Delays



- **LPV control of systems with variable-time delays**

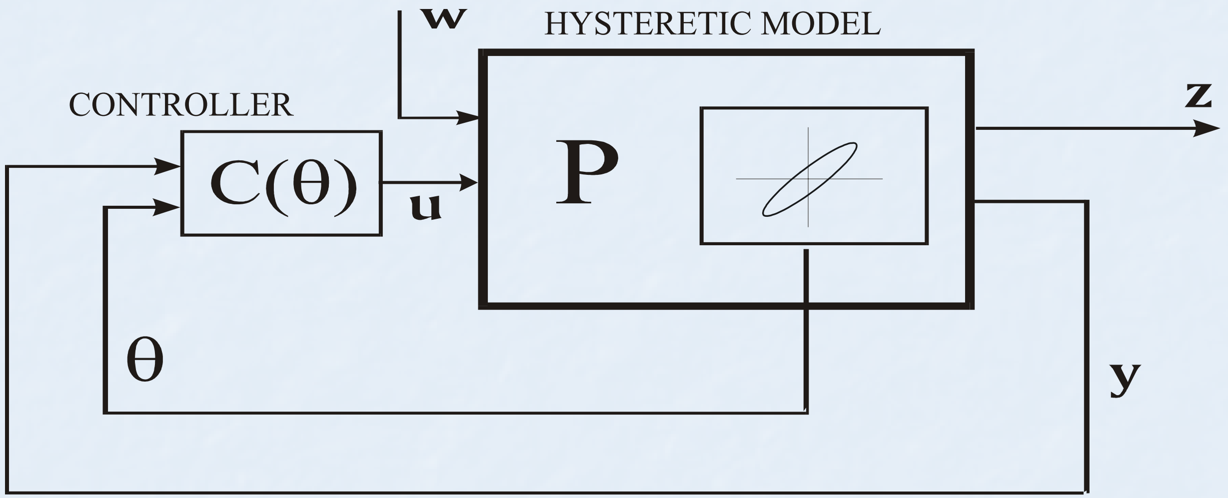
  Adapt the control law to the delay variability

Extensions: Fault-tolerant Control



- **LPV fault-tolerant control**
  Adapt the control law to sensor/actuator/sub-system failures.

Extensions: Control of Hysteretic Systems



- **LPV control of hysteresis**

  Adapt the control law to the current operating point of the hysteresis nonlinearity

Conclusions

- LPV control provides a systematic framework for optimized robust control of systems with variability and nonlinearities.
- The corresponding control synthesis is computationally effective allowing fast redesign
- The LPV approach can handle control design for a variety of challenging control problems in a unified way

Intelligent Systems Research & Education

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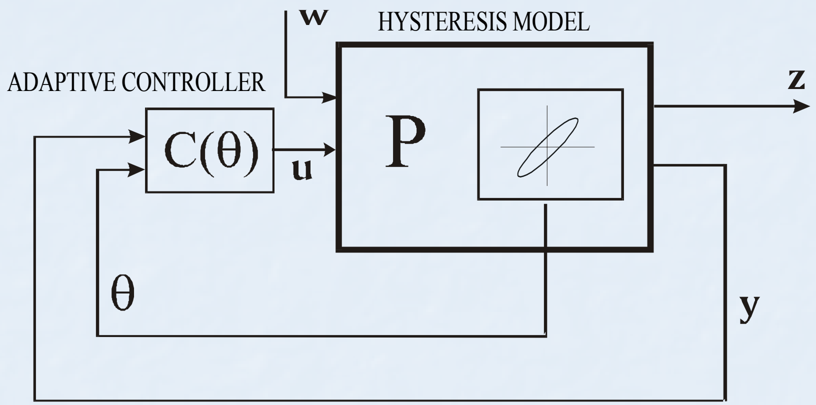
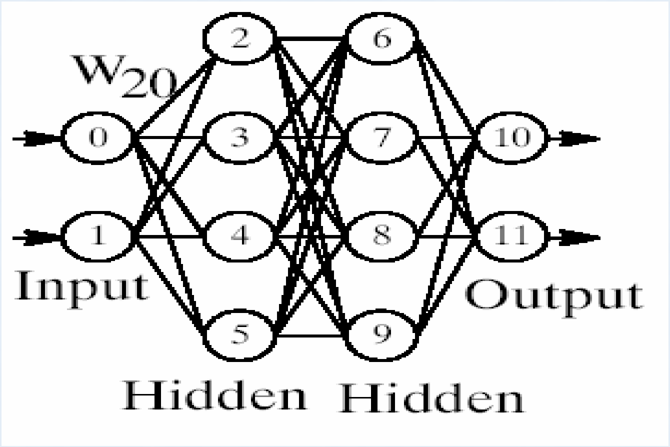
UH DSCL

Texas Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles

Development of Advanced Control Methods

- ***System Modeling and Identification***
- ***Advanced Control Design Methods***
- ***System Robustness to Uncertainty and Disturbances***
- ***Integrated System Design Optimization***
- ***Sensor and Actuator Selection and Placement***
- ***Fault Tolerant Control***





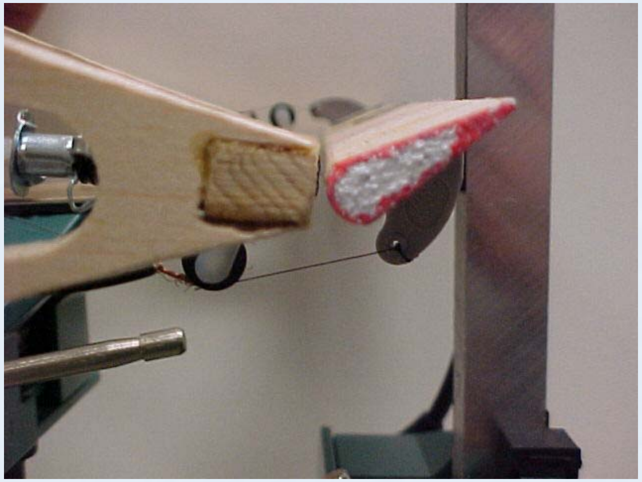
Engine and Automotive Control

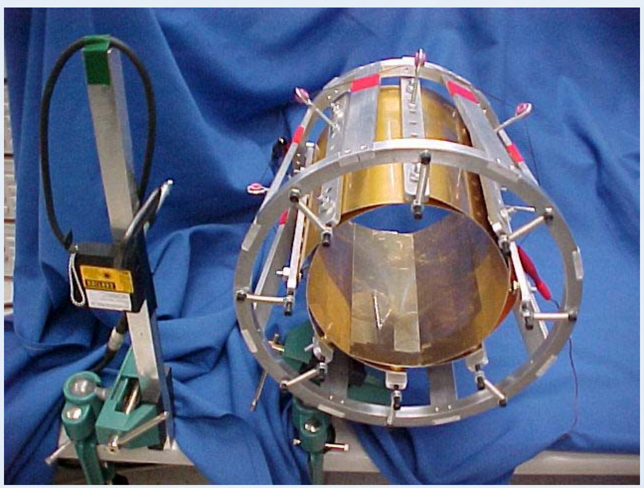
- *Advanced Adaptive Engine Control*
- *Air-Fuel Control for Emission Reduction*
- *Optimal Fuel Regulation*
- *Engine After-treatment Control*
- *Engine Performance Optimization*
- *Active Suspension Systems*

Structural Control

- *Active Vibration Suppression*
- *Microgravity Isolation*
- *Integrated Structure/Control Optimization*
- *Hysteresis Compensation*
- *Structural Fault Detection and Controller Reconfiguration*
- *Dynamic Systems Approximation and Model Order Reduction*

Smart Materials

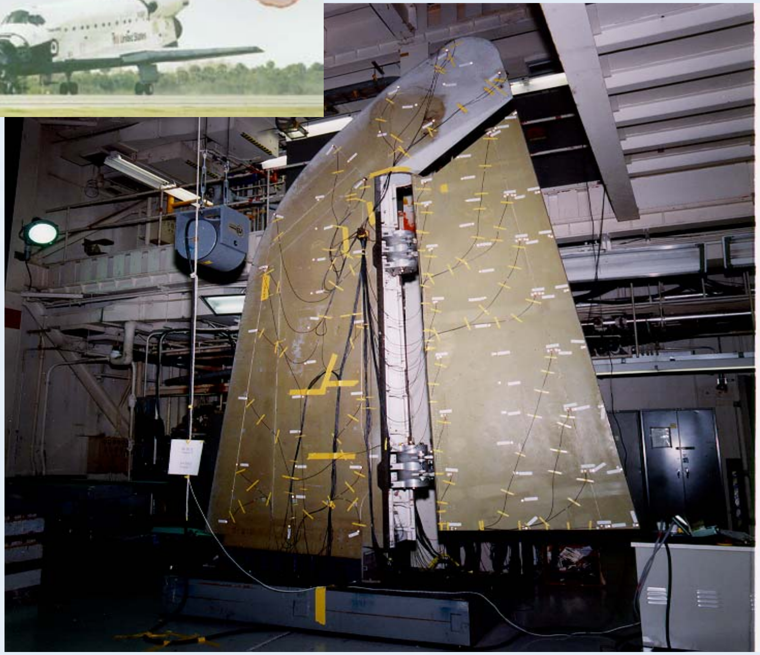


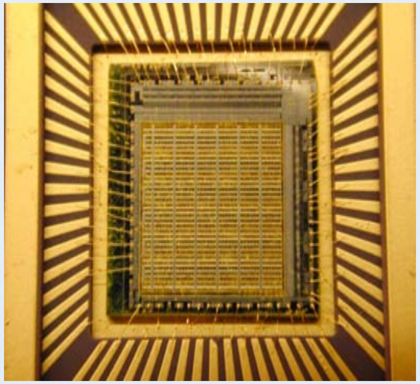


- Shape Memory Alloy (SMA) and Piezoceramic Actuation Control
- Smart Material Hysteresis Compensation
- Vibration Suppression Based on Smart Structures
- Smart Aircraft Engine Components
- Robotic and Space Applications of Smart Materials
- Smart Sensors and Actuators

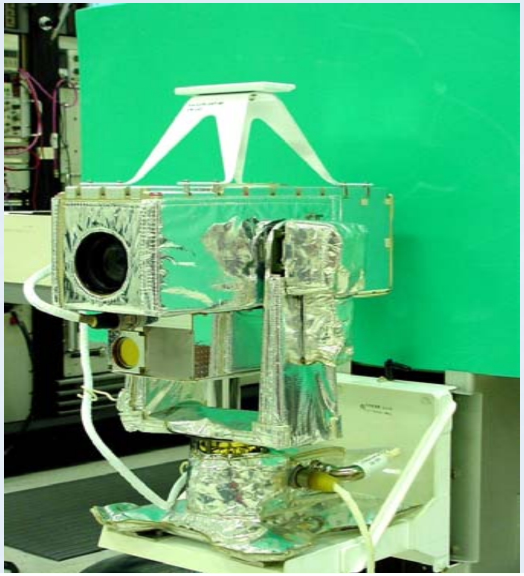
Structural Dynamics

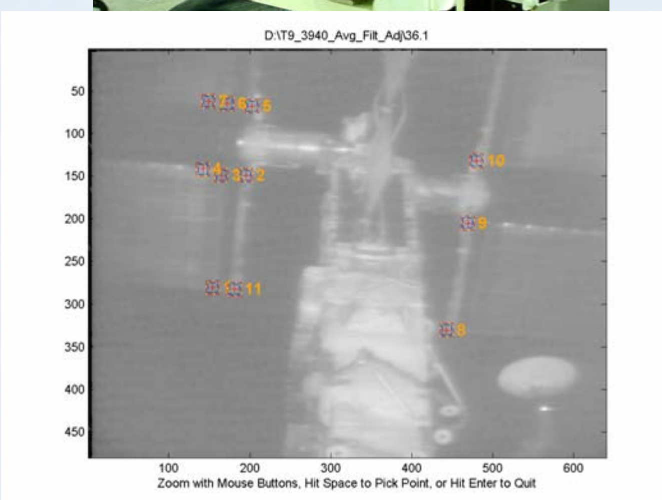
- *Vibration Isolation Design*
- *Vibration Testing*
- *Model Correlation*
- *Passive Vibration Reduction*
- *Structural Health Monitoring*
- *Impact detection, localization and magnitude estimation*
- *MEMS modeling and experimental characterization*





Sensing and Health Monitoring

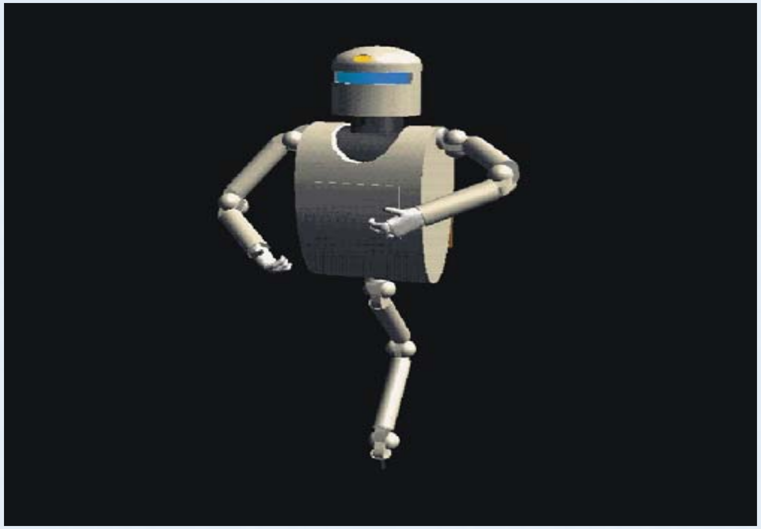




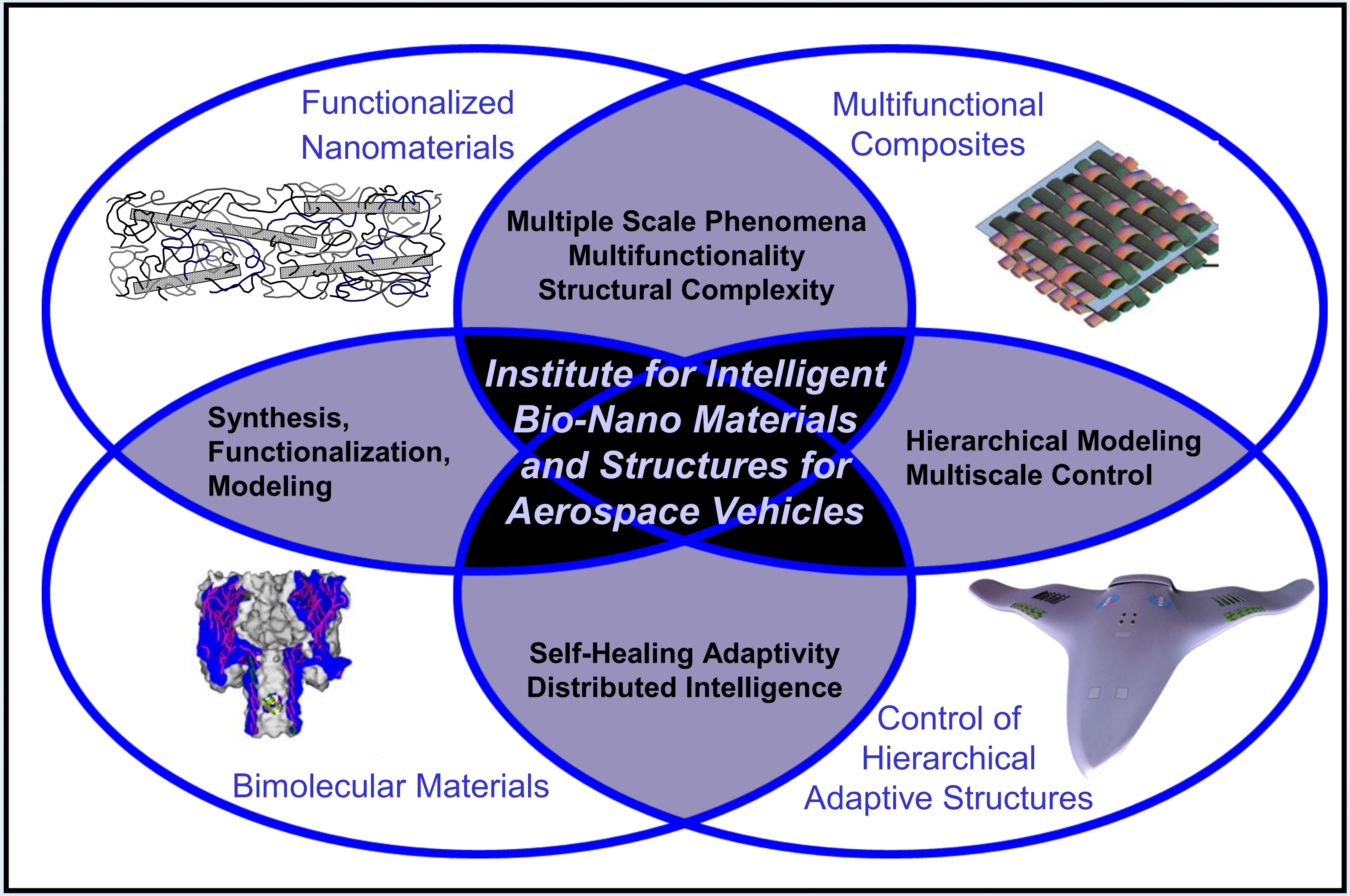
- *Sensor Development to Detect Motion*
- *Software Development to Process Images into Range and Range-Rate Information*
- *Use Information to Monitor Structural Integrity of ISS*
- *Sensor Health Management*

Robotics and Space Systems

- *Robot Dynamics*
- *Robot Control*
- *Telepresence and Teleoperation*
- *Vision-based Sensing*
- *Robot Motion Tracking and Motion Mapping*
- *Robotic Surgery*



NASA Center on Intelligent Aerospace Vehicles



UH Graduate Program in Aerospace Engineering

- *Interdisciplinary Engineering Program*
- *Awards M.S. (thesis/non-thesis) and Ph.D. degrees*
- *Core areas:*
  - *- Aerodynamics and Propulsion*
  - *- Structural mechanics and materials*
  - *- Dynamics and orbital mechanics*
  - *- Flight control and automation*
- *Part-time or full-time enrolment*
- *Some courses are offered at the UH-CL location*