Analysis of Control Architectures for a Fuel Cell Processor in a Fuel Cell Power Plant

Subbarao Varigonda
Mihai Huzmezan
Jonas Eborn
Scott Bortoff

Presented by:

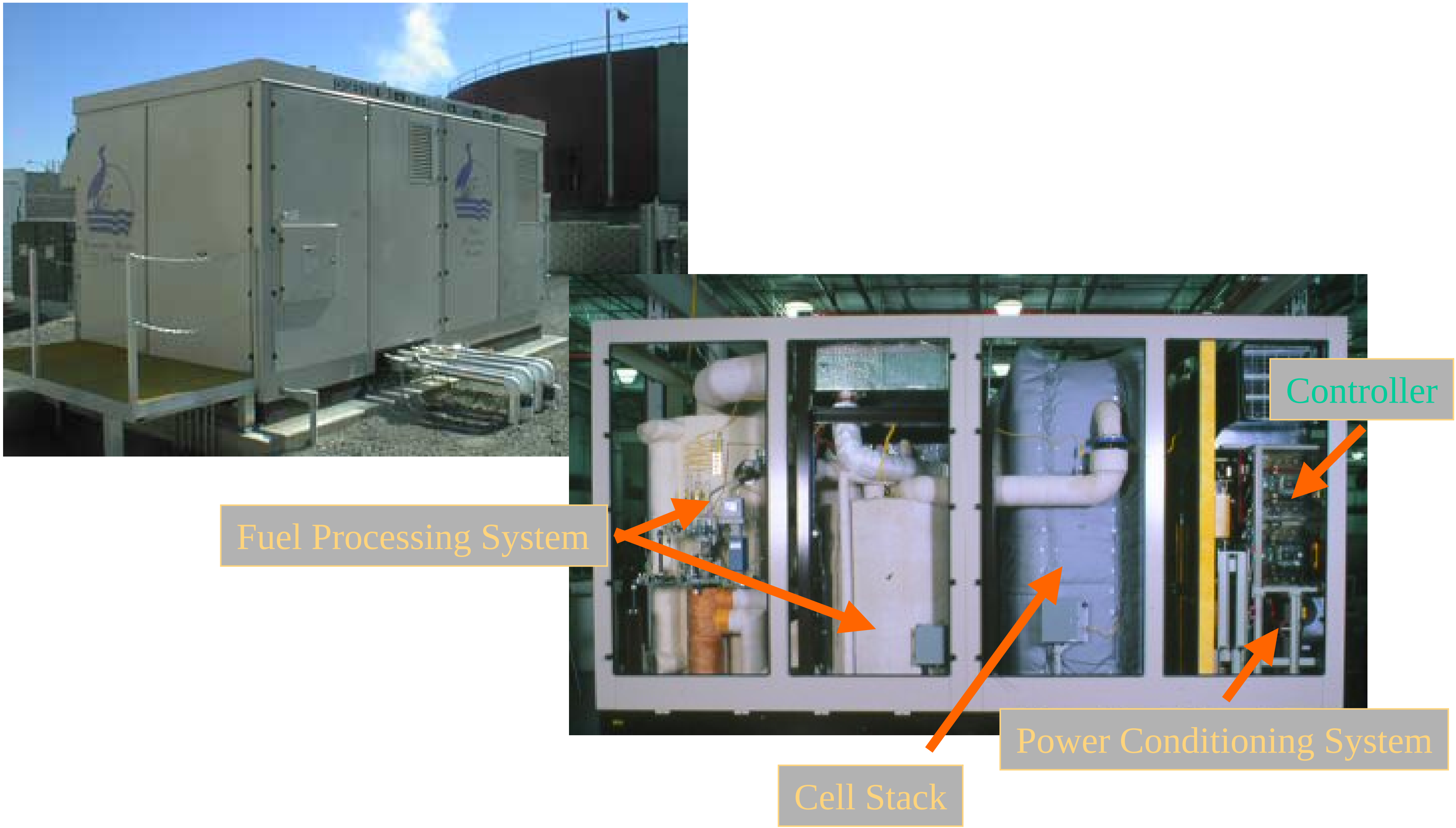
Mihai Huzmezan

United Technologies
Research Center

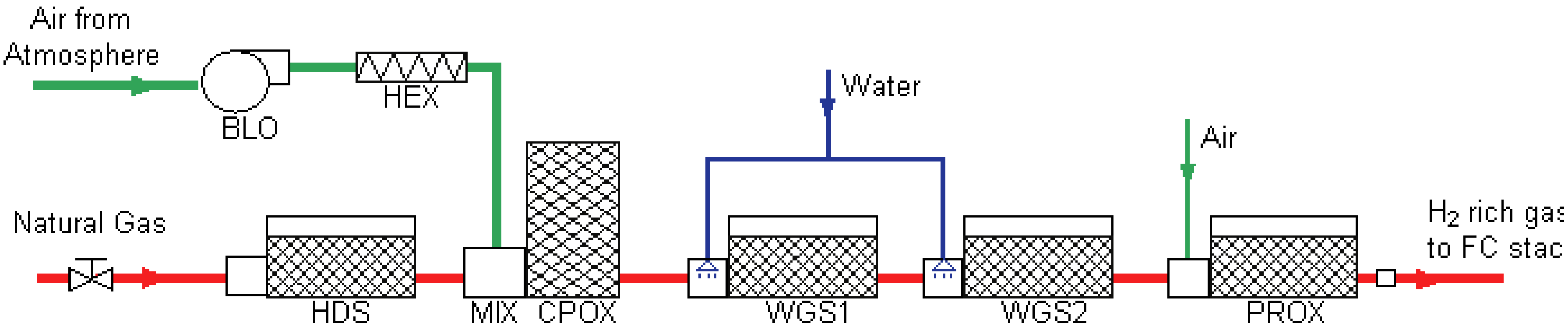
Talk Overview

- FPS problem setup (system, variables, challenges, etc.)
- Proposed solution for analysis
- Briefing on theory for proposed solution
- Comparative controller (legacy vs. advanced) performance assessment
- Conclusions

Typical Fuel Cell / Fuel Processing Unit Structure

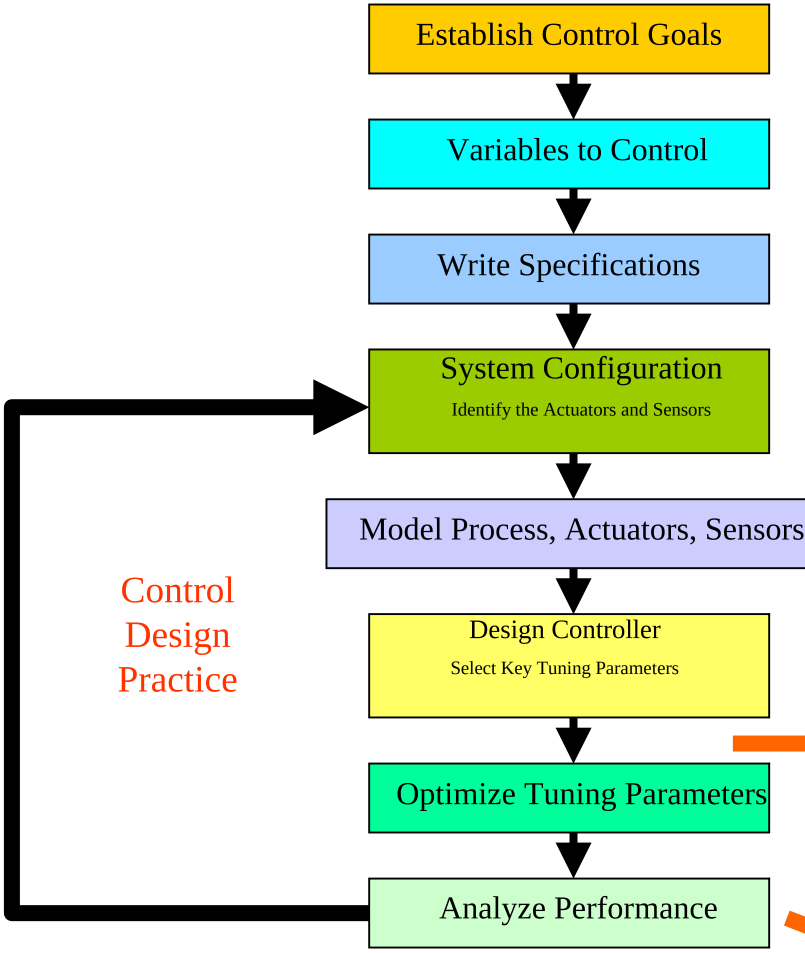


Typical Fuel Cell / Fuel Processing Unit Structure



- Catalytic Partial Oxidation (CPO) based fuel reforming is attractive due to system simplicity and efficiency
- Highly exothermic side reaction (FOX) with selectivity a strong function of O2/C ratio
- Risk of CPO catalyst damage if reactor overheats during transients
- Strong interactions between fuel and air
- Reliance on secondary measurements since sensors cannot be placed at the point of interest (e.g. CPO bed temperature and flow sensors)
- Nonlinear characteristics of plant, sensors and actuators

Control Design Practice



Establish Control Goals

Variables to Control

Write Specifications

System Configuration
Identify the Actuators and Sensors

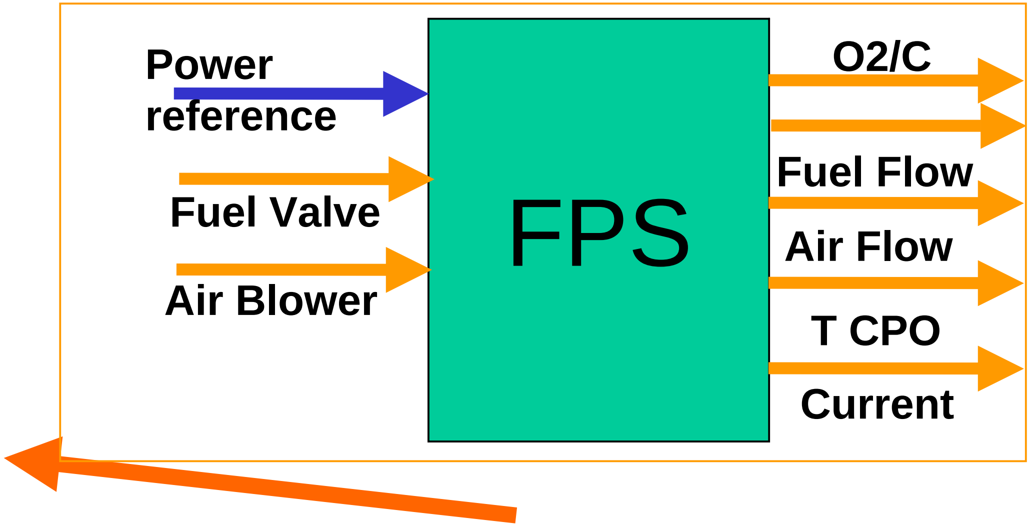
Model Process, Actuators, Sensors

Design Controller
Select Key Tuning Parameters

Optimize Tuning Parameters

Analyze Performance

Control
Design
Practice

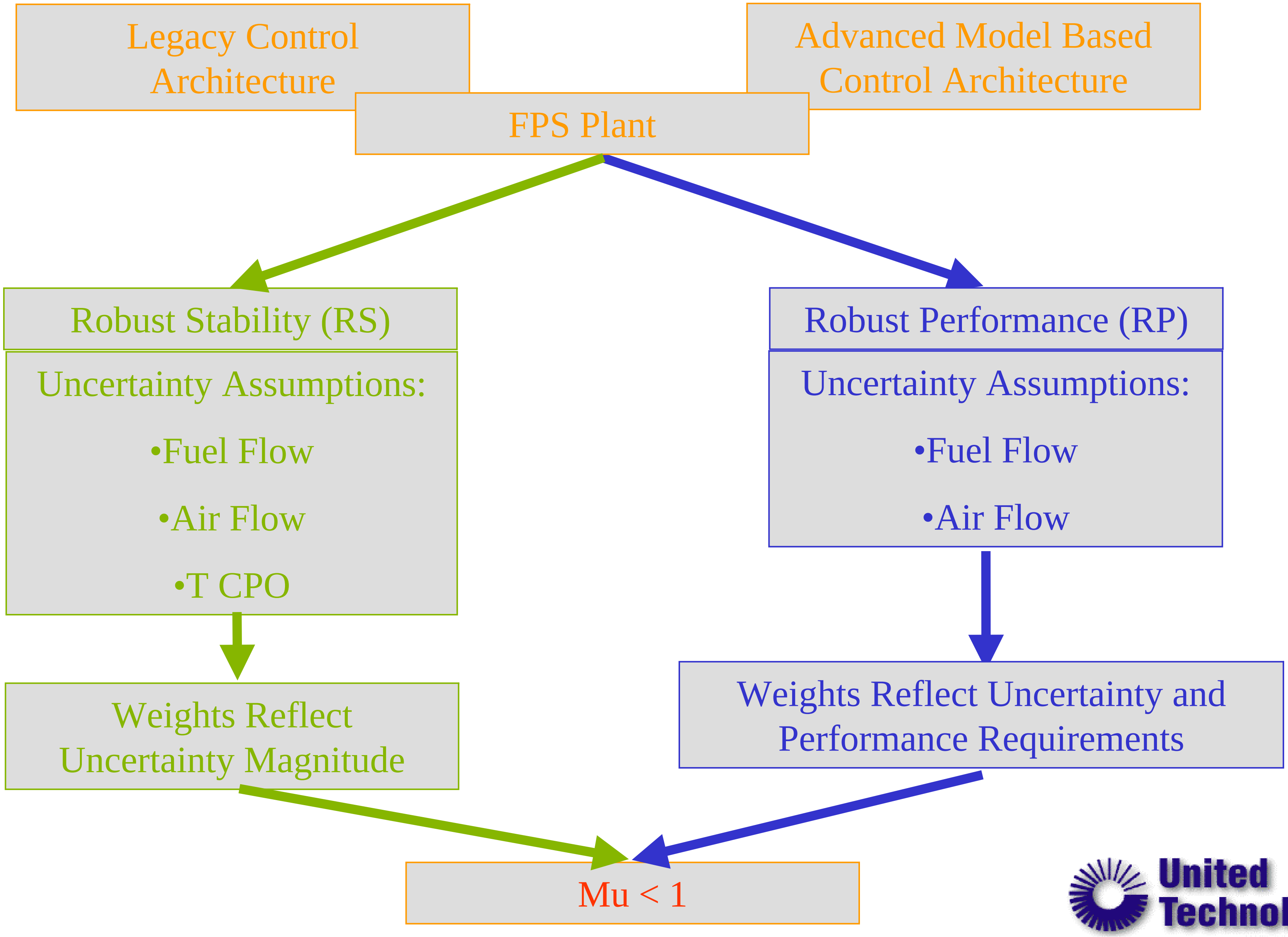


Two different methods were employed for controller design

Control Architecture Performance Analysis

(FOCUS OF TALK)

Analysis approach



Legacy Control Architecture

Advanced Model Based Control Architecture

FPS Plant

Robust Stability (RS)

Uncertainty Assumptions:

- Fuel Flow
- Air Flow
- T CPO

Weights Reflect Uncertainty Magnitude

Robust Performance (RP)

Uncertainty Assumptions:

- Fuel Flow
- Air Flow

Weights Reflect Uncertainty and Performance Requirements

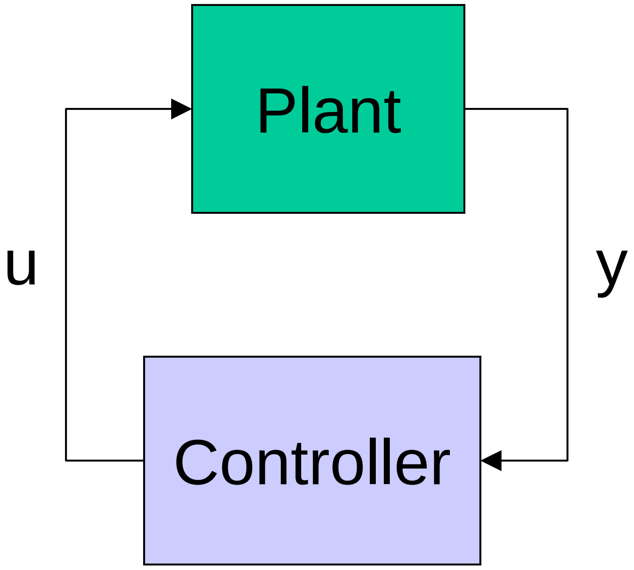
Mu < 1

Nominal Stability and Nominal Performance - A Theory Briefing

Design with nominal plant model does not guarantee robustness

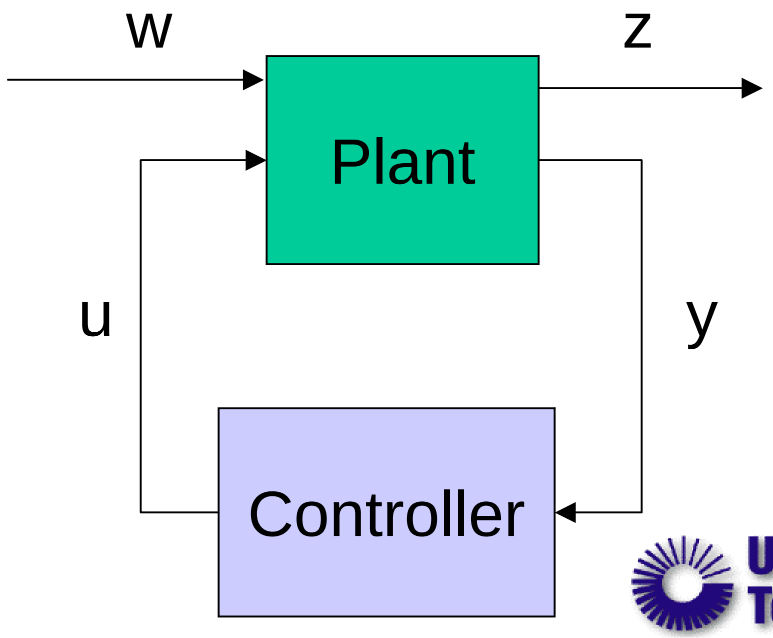
- Nominal stability → Requires only closed loop stability with given plant
- Nominal performance → Requires closed loop stability and disturbance rejection with given plant
- Model uncertainty can destabilize the system or reduce performance

[P,C] stable



[P,C] stable and

$$\|T_{zw}\| < 1$$



Robust Stability - A Theory Briefing

Stability in the presence of model uncertainty

- Robust stability → Requires stability for given class of plants
- Uncertainty model → Defines a class of plants centered around a nominal plant

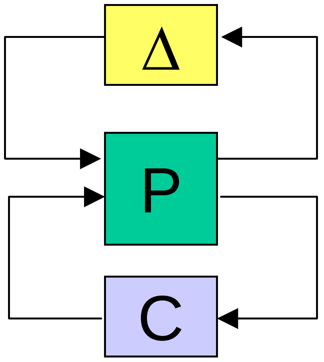
$$P = P_0(1+W\Delta) \qquad\qquad P = P_0 + W\Delta$$

- Structured singular value (μ) → Determines robust stability of the interconnection [P,C]

$$\mu(G,\Delta_{class},\omega)^{-1} = \inf_{\Delta\in\Delta_{class}} \|\Delta\|_\infty \text{ such that } \det(I - G\Delta) = 0$$

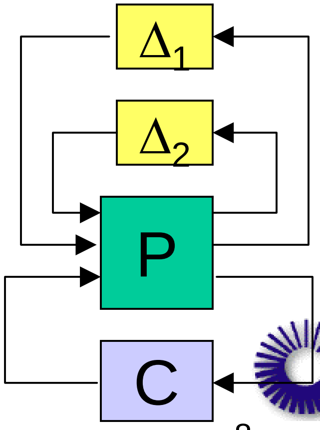
- Robust stability can be guaranteed iff: $\mu < 1$

Robust stability problem

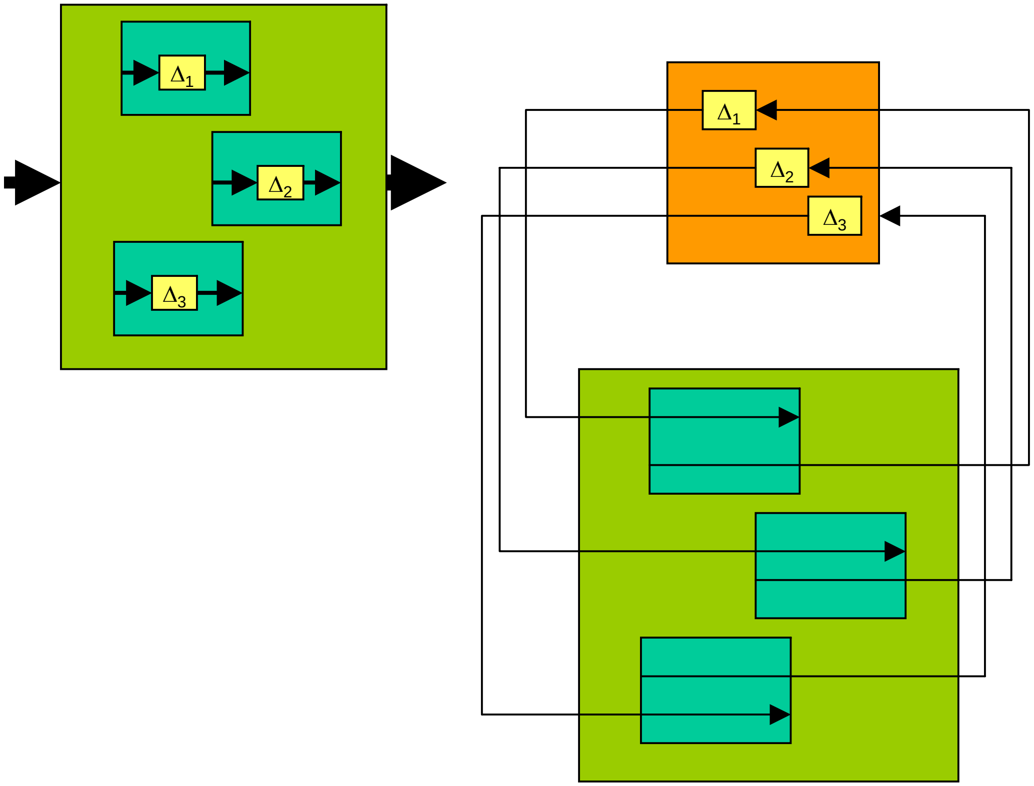


$$\Longrightarrow \quad \Delta = \begin{bmatrix} \Delta_1 & 0 \\ 0 & \Delta_2 \end{bmatrix}$$

Structured uncertainty



Structured Uncertainty Used in Closed Loop Analysis - ***A Theory Briefing***



Model uncertainty is represented as interconnections with a delta block

Parametric (real) vs. non-parametric (complex) uncertainty

Structured (block diagonal Δ) vs. unstructured (full block Δ) uncertainty

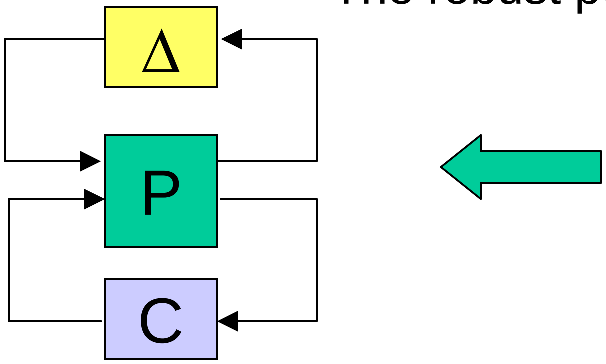
Robust Performance - A Theory Briefing

Stability and performance in the presence of model uncertainty

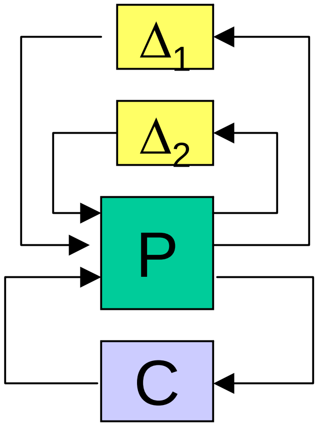
- Robust Performance → Require stability and performance for given class of plants
- Performance specifications can be represented as interconnection with a delta block
- Delta blocks now represent both model uncertainty and performance requirements
- Robust performance test = Robust stability test with structured uncertainty
- Structured singular value (μ) framework still applies
- Robust performance can be guaranteed iff: $\mu < 1$
- Computation of *mu* can be performed with various by various algorithms:

PSV, MuOpt, Perron, Osborne, Slicot

The robust performance problem



$$\Delta = \begin{bmatrix} \Delta_1 & 0 \\ 0 & \Delta_2 \end{bmatrix}$$



Setup for Robustness Analysis of Air-Fuel Control

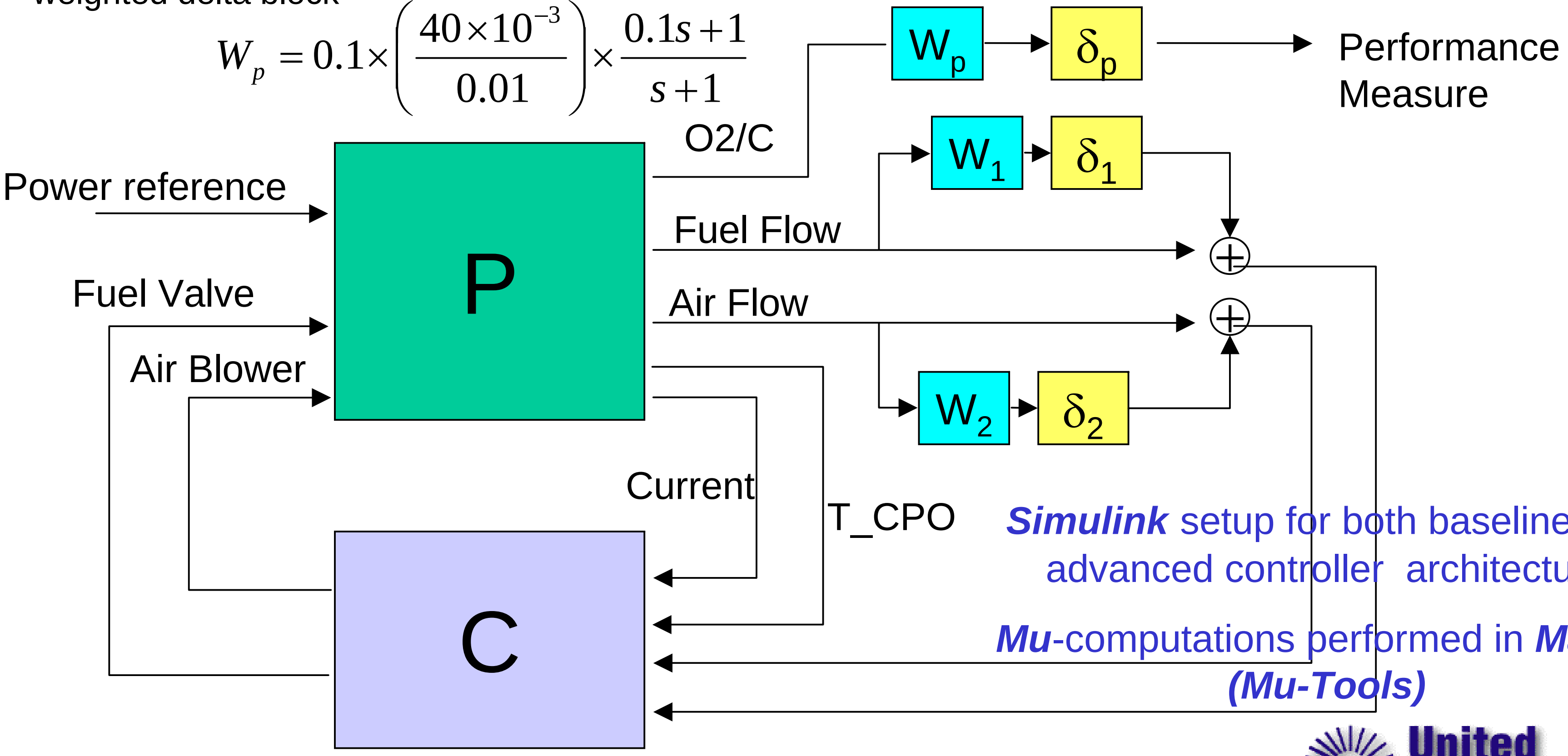
Linear plant model with structured multiplicative uncertainty

- Fuel and air flow uncertainty represented by weighted delta blocks

$$W_1 = W_2 = 0.05 \times \frac{2s+1}{s+1}$$

- Performance requirement (disturbance rejection from P_ref to O2/C) is represented by another weighted delta block

$$W_p = 0.1 \times \left(\frac{40 \times 10^{-3}}{0.01} \right) \times \frac{0.1s+1}{s+1}$$



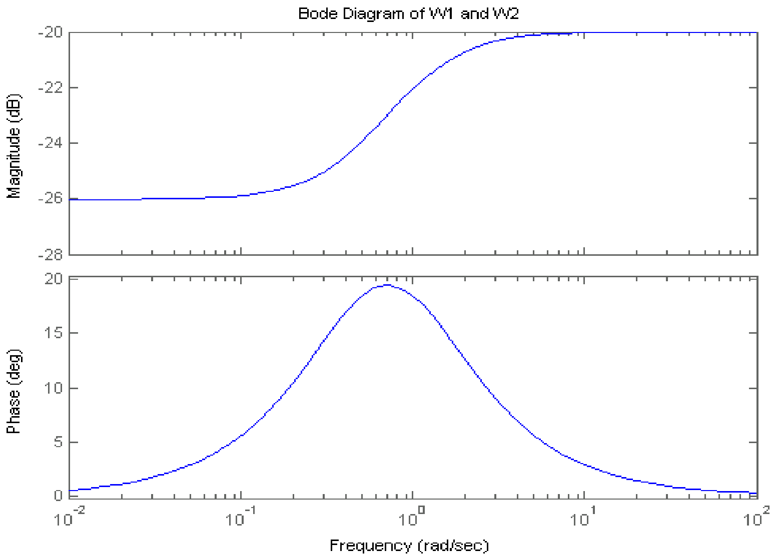
Simulink setup for both baseline and advanced controller architecture

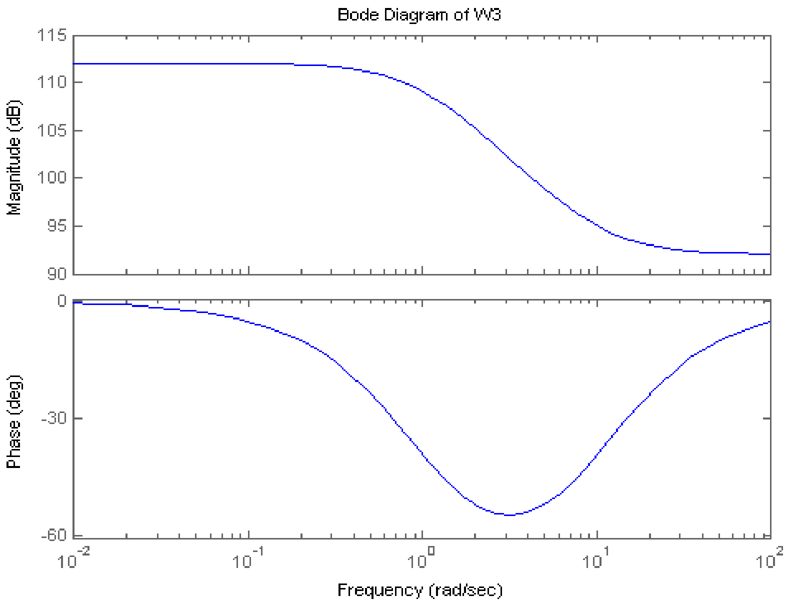
Mu-computations performed in ***Matlab (Mu-Tools)***

Weights selection

Linear plant model with structured multiplicative uncertainty

- Error in flows is 5% at steady state and 10 % at 1 [rad/s]: $W_1 = W_2 = 0.05 \times \dfrac{2s+1}{s+1}$
- Power reference to O2/C disturbance rejection weight: $W_p = 0.1 \times \left(\dfrac{40 \times 10^{-3}}{0.01} \right) \times \dfrac{0.1s+1}{s+1}$
- O2/C transient performance allowance = 10x steady state



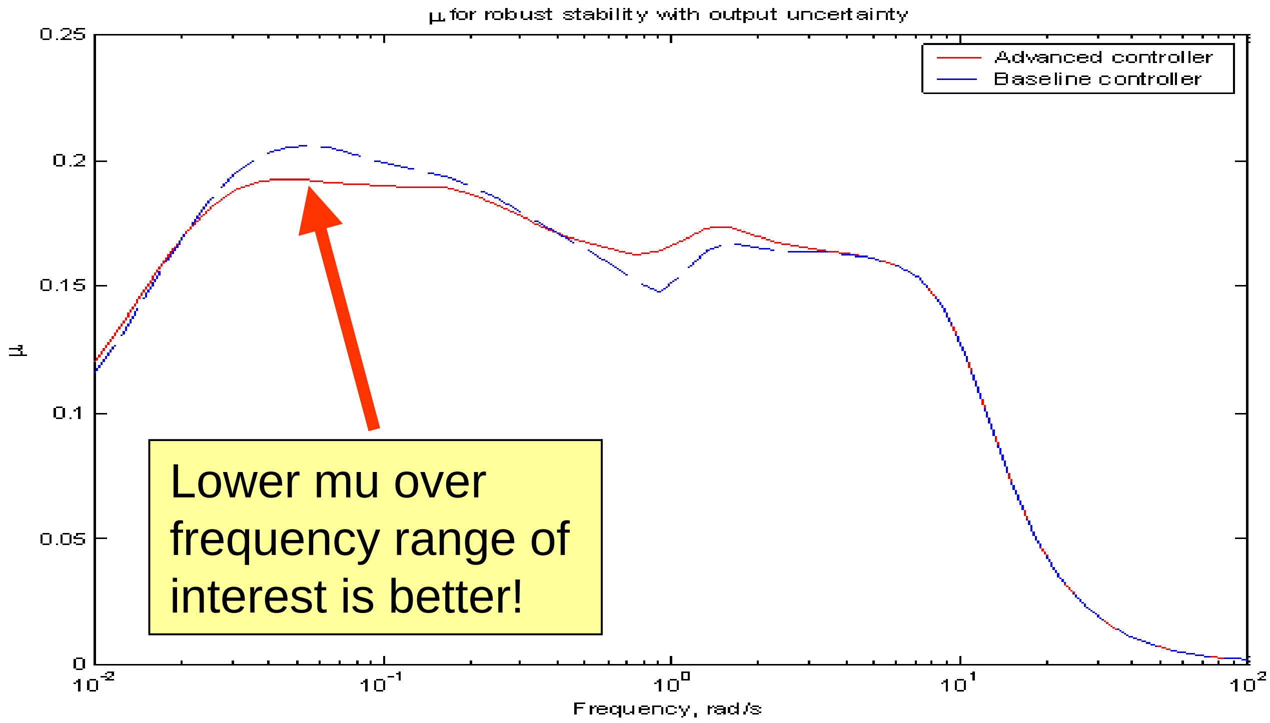


Robust Stability Study

Advanced controller has a better stability margin

- Diagonal structured, non-parametric, multiplicative uncertainty: $P = (1 + W\Delta)P_0$

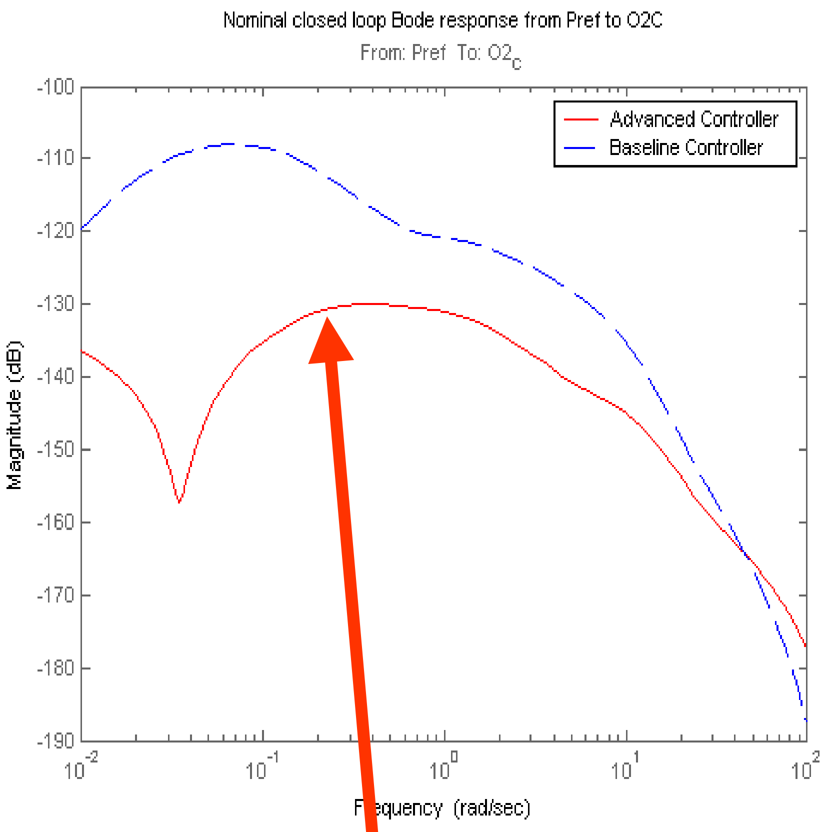
  in **Fuel Flow**, **Air Flow** and **T CPO** (catalytic partial oxidation reactor) outputs
- Uncertainty in **T CPO** at lower frequencies (1 decade lower than that in flows)
- Multivariable robustness margin = $1/\mu$

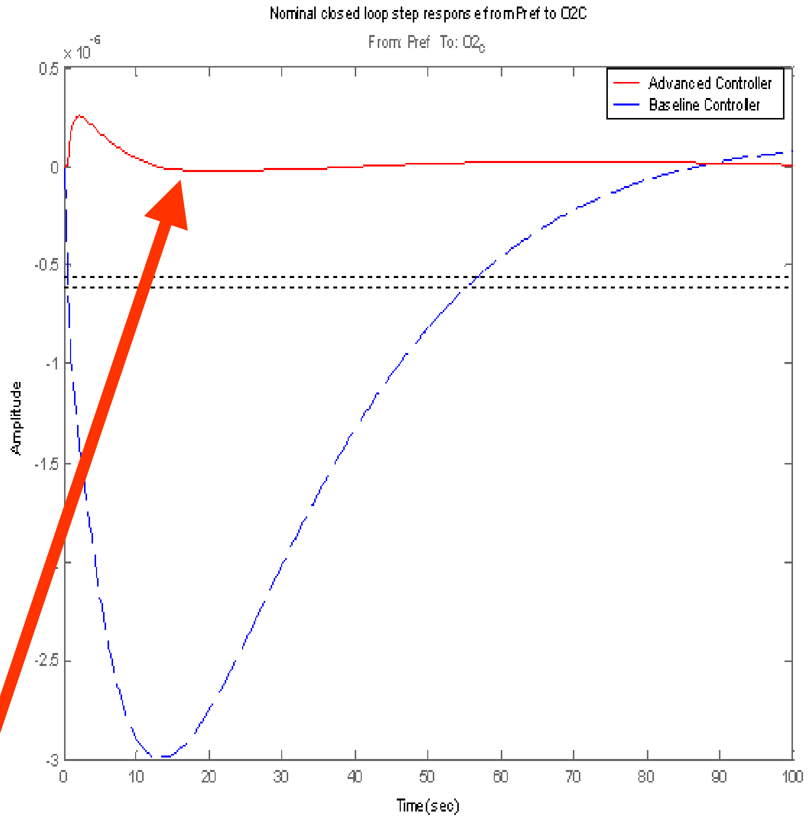


Lower mu over frequency range of interest is better!

Disturbance Rejection Performance

Advanced control improves disturbance rejection with nominal plant

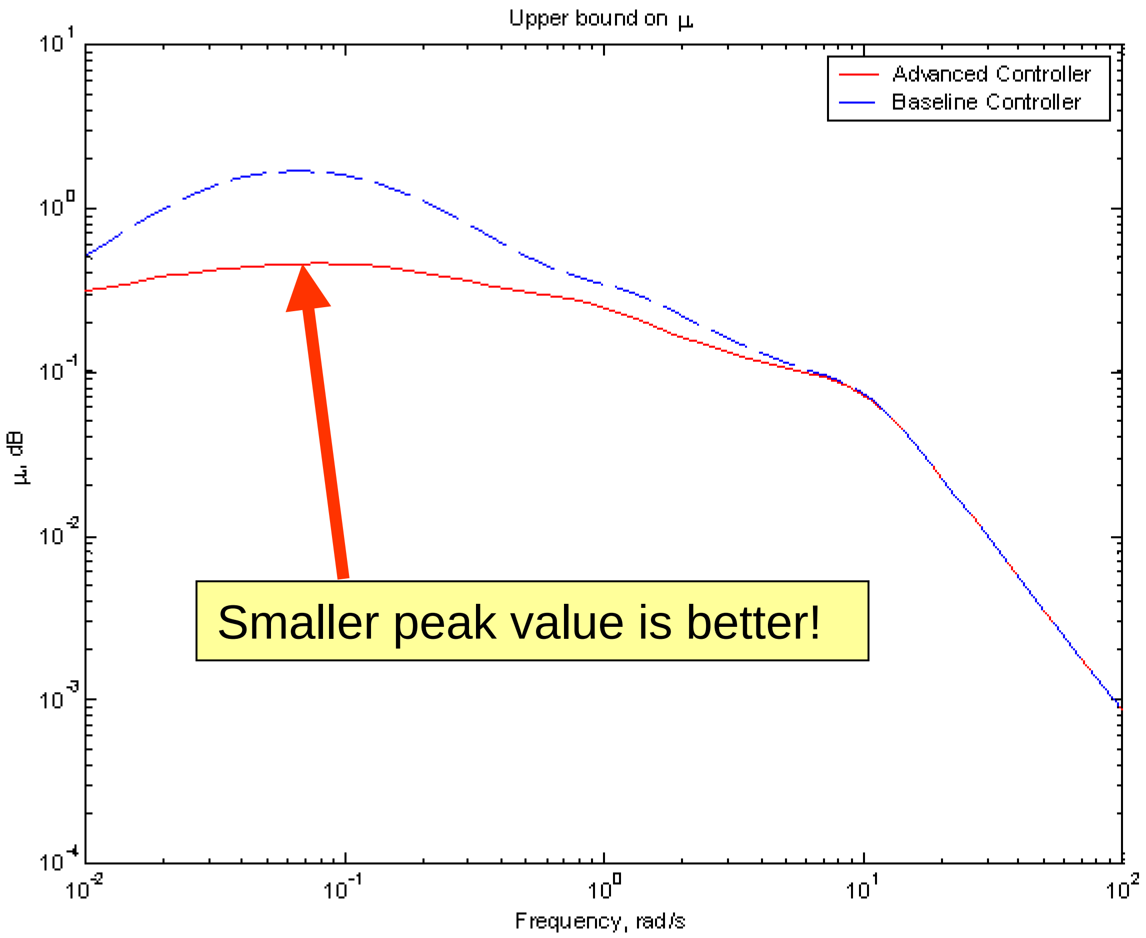




Lower gain from P reference to O2C is better!

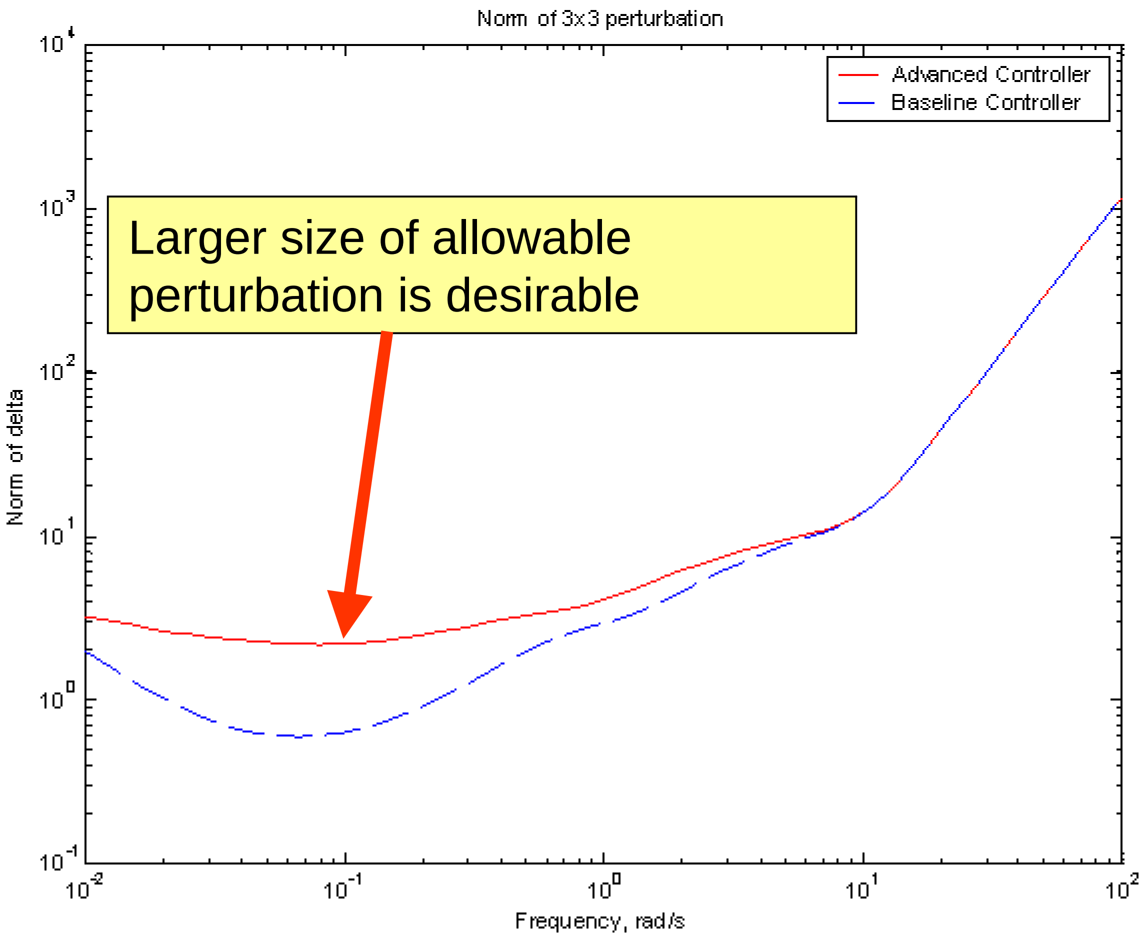
Mu-Analysis

Advanced controller gives better robust performance than the baseline controller



Smaller peak value is better!

Norm of allowable worst case perturbation (3x3 delta)

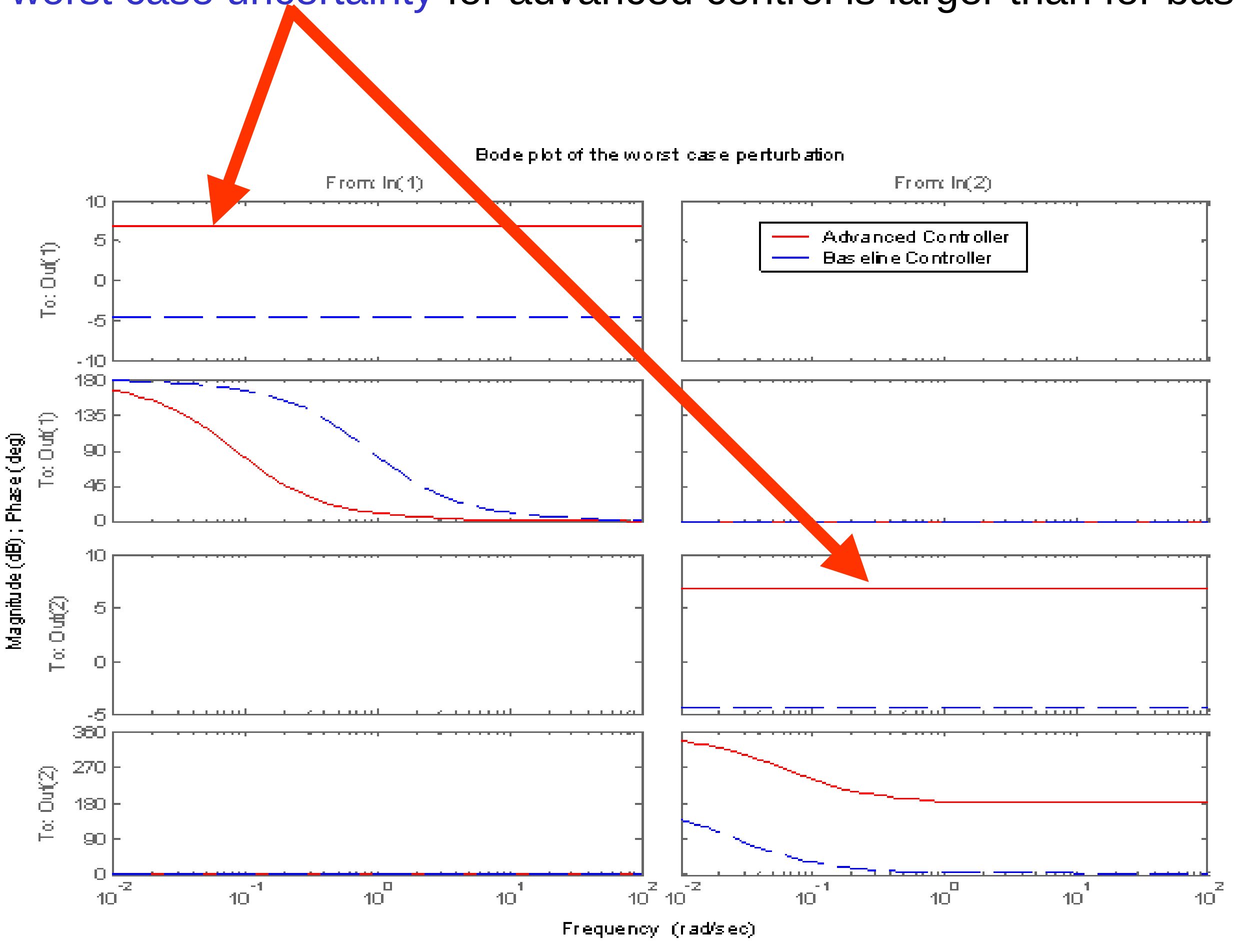


Larger size of allowable perturbation is desirable

Analysis of Control Architectures for a Fuel Cell Processor in a Fuel Cell Power Plant

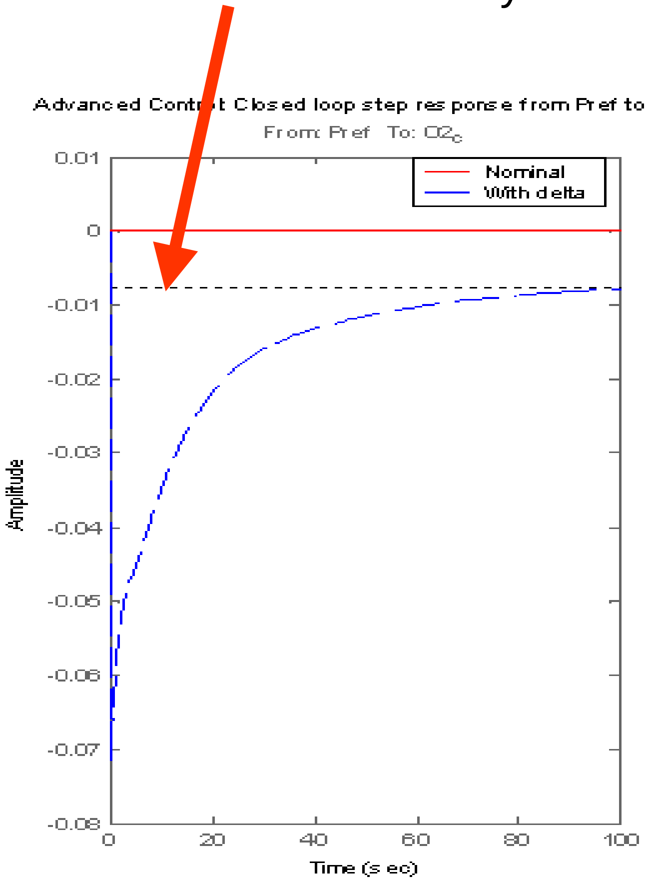
Frequency response of the worst case model uncertainty

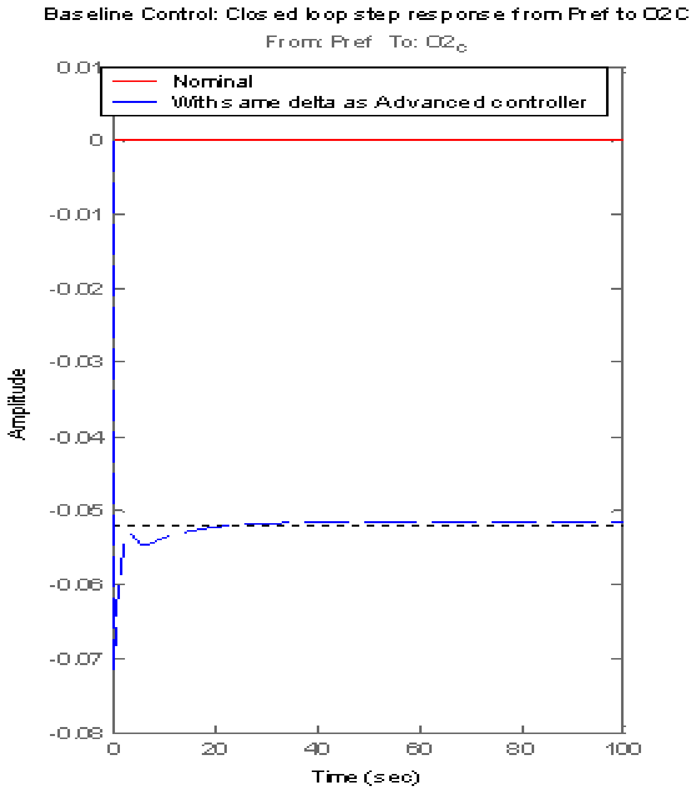
- Worst case uncertainty is when robust performance objectives cannot be attained
- Allowable worst case uncertainty for advanced control is larger than for baseline control



Closed loop time response with the worst case uncertainty

- Worst case is when robust performance cannot be attained
- Allowable worst case uncertainty for advanced control is larger than for baseline control

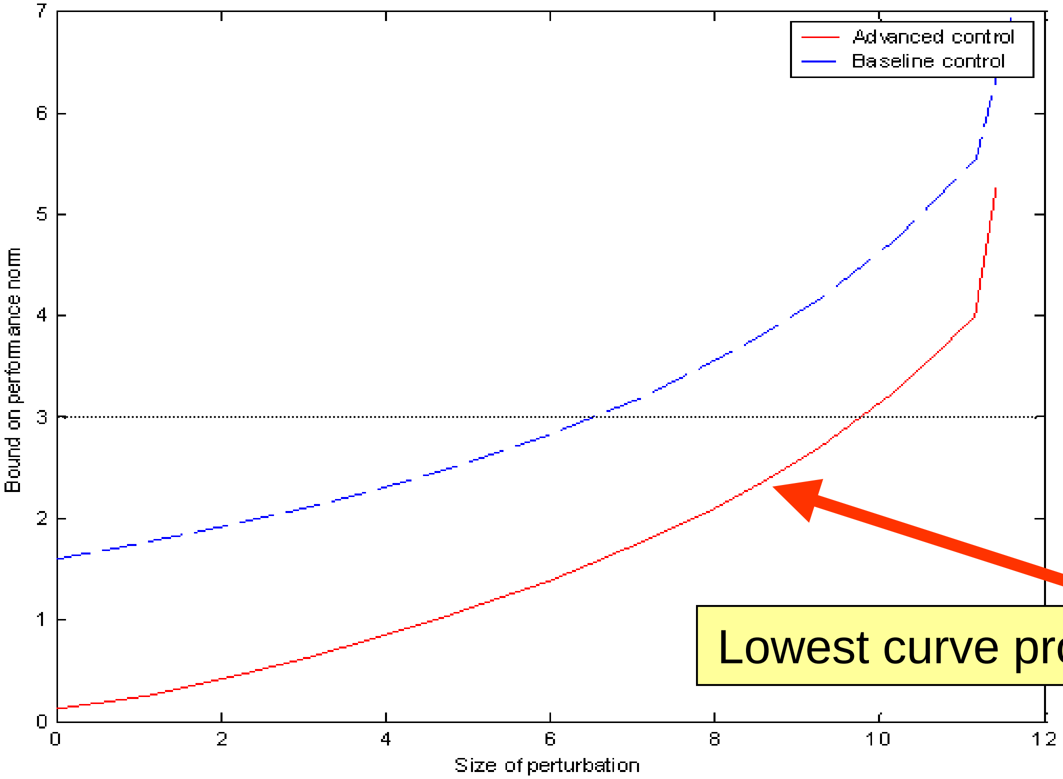




Analysis of Control Architectures for a Fuel Cell Processor in a Fuel Cell Power Plant

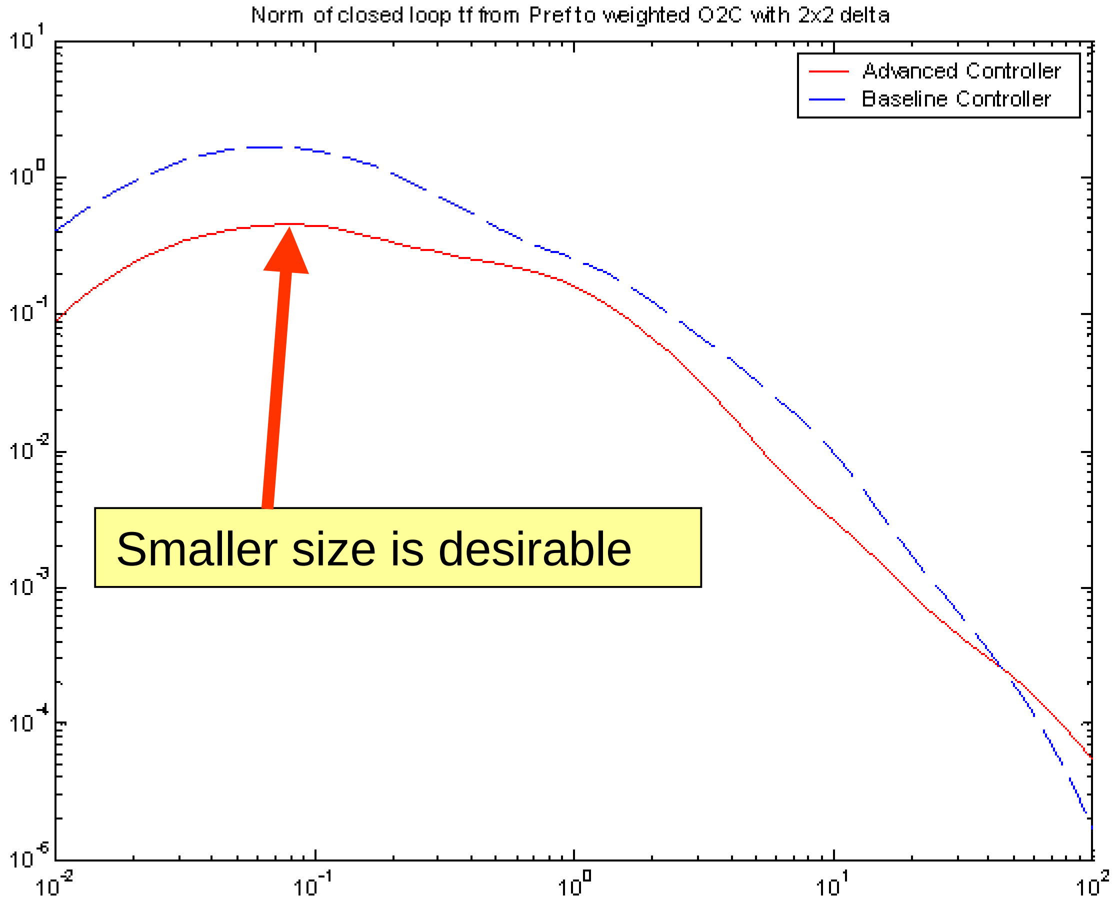
Performance degradation as a function of model uncertainty

- Gradual deterioration in achievable robust performance as model uncertainty is increased
- Performance degradation is less for advanced control than for baseline control



Lowest curve provides tightest bound!

Size of the closed loop transfer function from Power reference to O2/C



Smaller size is desirable

Conclusions

- Proposed analysis = standard work
- Model based control tools are used successfully for assessment
- Controller (legacy vs. advanced) performance evaluation favors the advanced controller
- This is just a possible path for analysis
- Mu analysis and synthesis enable robust control design

Alternative Methods for: Uncertainty Propagation Analysis

- Mu analysis and synthesis considers worst case scenario
- Additional information about uncertainty (e.g., probabilistic knowledge) is not utilized
- Extensions of robust control methods to account for probabilistic notions of uncertainty pursued by Barmish et al (Wisconsin) and Zhu (Caltech)
- Direct characterization of uncertainty is also possible and beneficial