Servo Control of a Turbine Gas Metering Valve by Physics-Based Robust Controls (μ) Synthesis

Dr. Peter M. Young
Prof. Electrical Engineering
Colorado State University
pmy@colostate.edu

Dr. Kamran Eftekhari Shahroudi
Manager of Analytical Group, Woodward
keftek@woodward.com
Systems Design and Management Fellow, MIT
keftek@sloan.mit.edu

Overview

1. Quick Summary of Robust Controls (μ) Theory
2. Limitations of Current Robust Controls Tools
3. Practitioners Breakthrough: The Physics-Based μ-Synthesis
4. Industrial Application to GS16 Turbine Valves
    - Results
    - Practical Hurdles
    - Experienced Advantages
    - Remaining Problems
5. Recommendations for Future Tool Improvements
6. Sample Woodward Products: Aircraft Engine and Reciprocating Engine Product Portfolio.

1.1 Picture History of Controls by Zhou et. Al.

PID’s
Gain/Phase Margin
Simple but fiddly!
Ideal when:
- plant info is scarce.
- performance not critical.
- inverse of plant is close to a PID!

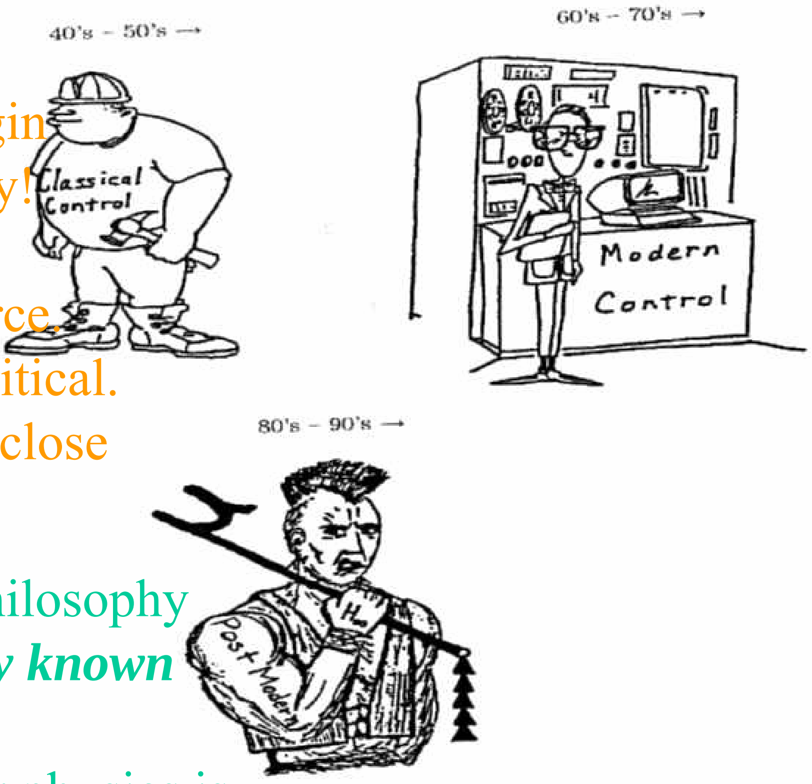


Figure 1.1: A picture history of control

State Space
Model/Observer Based
Ideal when:
- MIMO
- plant info is abundant.
- performance is critical at specific conditions.

Robust Design Philosophy
Ideal for ***partially known systems***:
- nominal low order physics is known.
- uncertainties, variations and disturbances can be bounded.
- performance is critical over a wide range of conditions.

Cartoons from the standard text book ***Robust & Optimal Control*** by Zhou et. Al.

1.2 Robust Controls: μ-Synthesis & Analysis

- Basic math framework: Doyle et. Al. ~1988.
- MATLAB® tools ~ 1995.
- Similar to 6σ philosophy
  - Design a controller to make the system performance and stability insensitive to bounded operational and behavioral variations by design.
  - Upfront Robust Design philosophy is at the core of this approach.
- Find a controller with guaranteed stability and performance margins subject to bounded uncertainties.
- μ- Analysis is powerful for linear systems:
  - Can use it to assess robustness no matter how the controller was synthesized.
- μ- Synthesis has issues because outputs a “Magic” controller:
  - Controller states are not physically tractable.
  - High order controller needs reduction.

1.3 Robust Controller Design Setup

Generalized Plant: P
- Fuel Metering System
- Includes Desired Performance

Uncertainties: Δ
- Unmodeled Dynamics
- Sensor Limitations

P Δ Combinations:
- Family of Plants

Controller: K
- MIMO
- Sensor Input Vector y
- Controller Output Vector u

Disturbances: w
- Load Disturbances
  - Friction and Flow Forces
  - Commands

Penalties: z
- Tracking Error
- Control Energy

Objective of μ-Synthesis:
- Design For Worst Case Signals and Systems -> Robust Performance
- Minimize the close loop energy gain from w to z over all frequencies for the whole family of P Δ plants
- Locate the easiest way (smallest Δ) to perturb performance and stability.

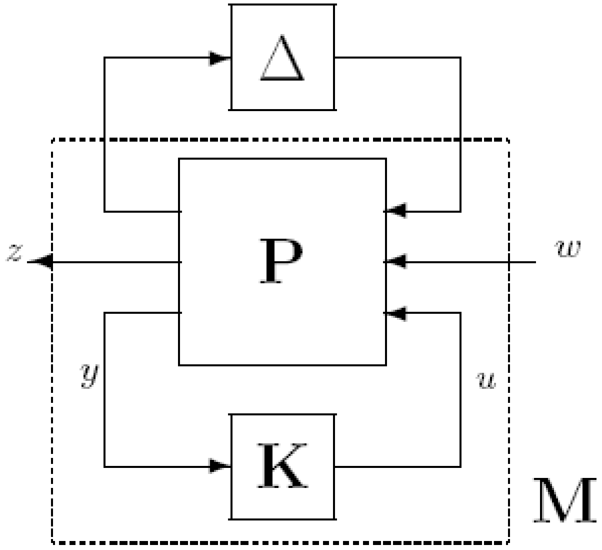


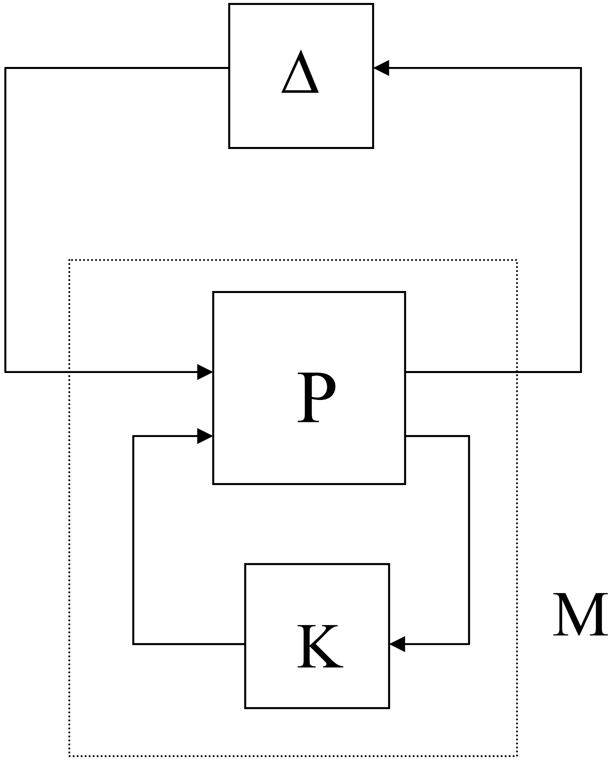
Fig. 1. Problem setup for μ synthesis

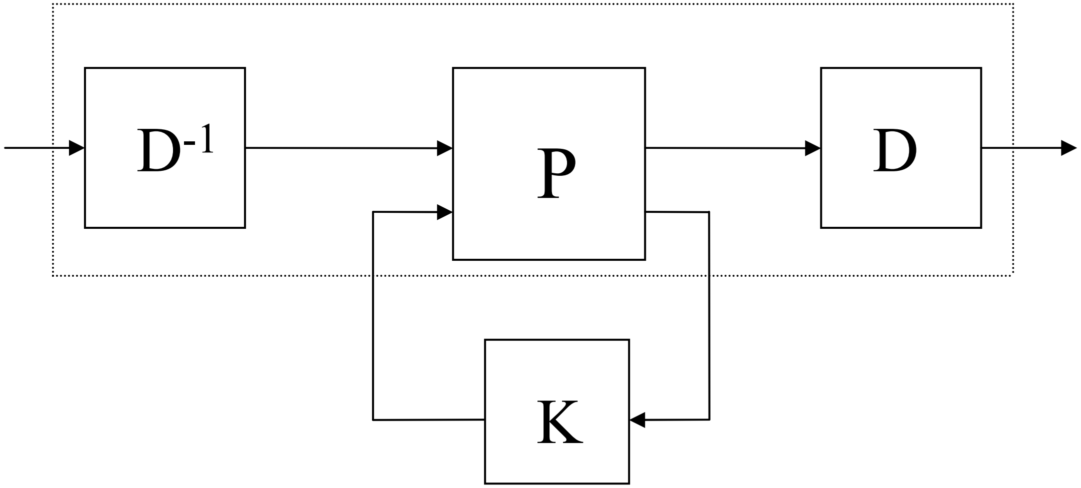
1.4 Powerful Machinery Under the Hood

μ = 1/(size of the smallest destabilizing perturbation)

μ Synthesis:

$$\inf_{K-\text{stabilizing}} \left(\inf_{D} \|DMD^{-1}\|_\infty \right)$$

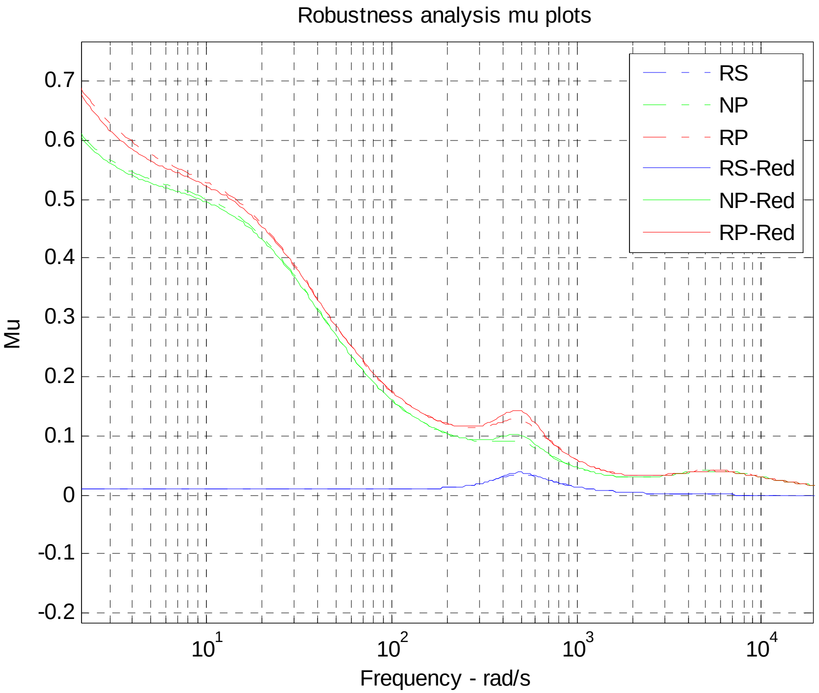




Compute D: μ Problem ↔ Compute K: H_∞ Problem

2.1 Basic Limitations of Current Robust Controls Tools

- Basic math theory is sound but the tools output a controller that is physically not tractable or “Magic”.
- The Synthesized controllers are high order, complex and not directly practical for many applications.
- Many (if not most) real plants are non-linear, but the theory and tools are purely linear.
- Not clear where to add nonlinear compensation
- Design weights used to drive synthesis are not physically meaningful.
- Hard to interpret what μ values really mean!



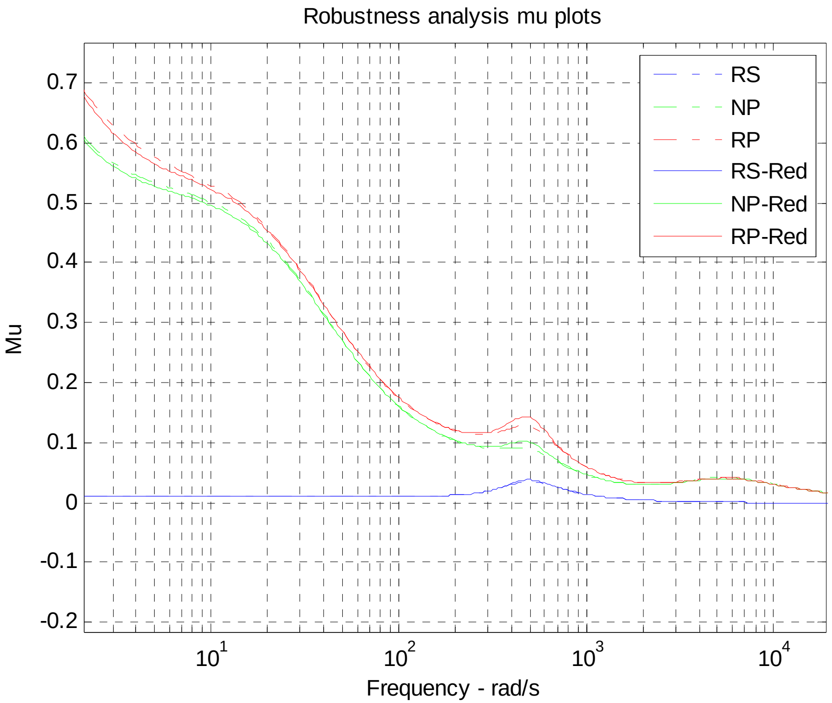
2.2 Practical Limitations of Current Robust Controls Tools

- The complete controller design process undefined.
- μ values do not enable NPI team interdisciplinary collaboration.
- Visualization of results and trade-offs and comparison with other controllers.
- How to convince OEM of safety critical machinery to trust this controller.
- How to debug a problem in the field or during development when the plant states with physical meaning are not available.
- No features to enable Diagnostics and Prognostics.

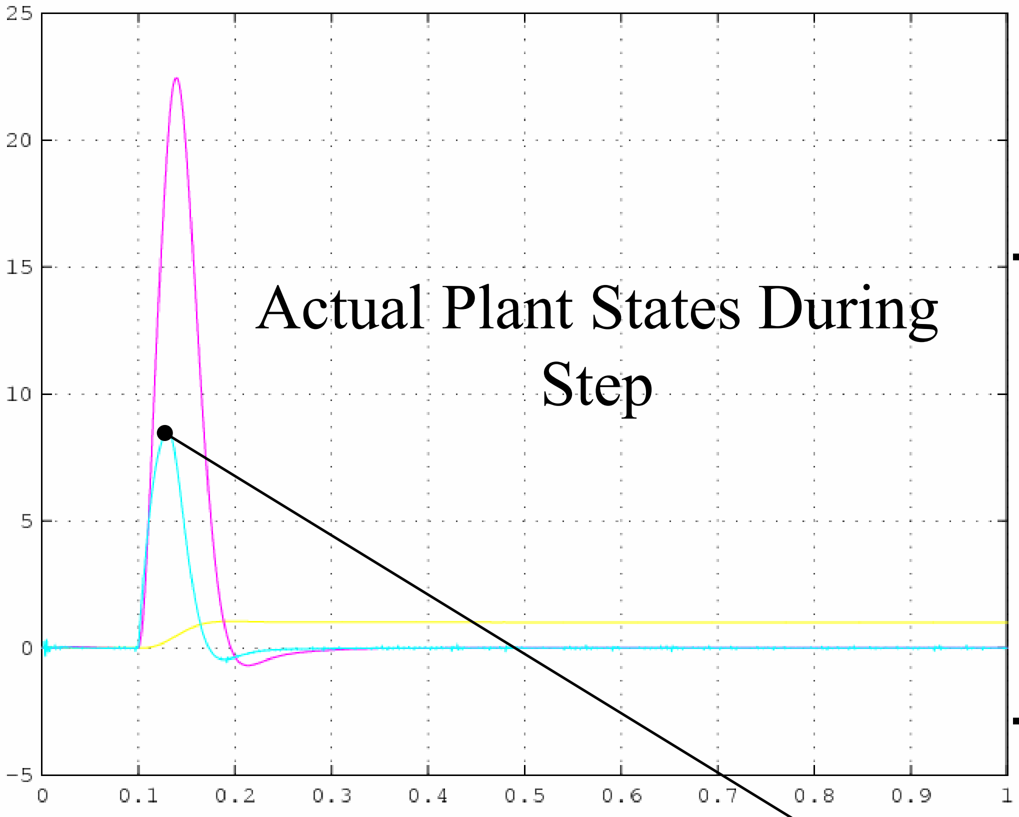
3.1 Physics Based μ-Synthesis: A practitioner's breakthrough

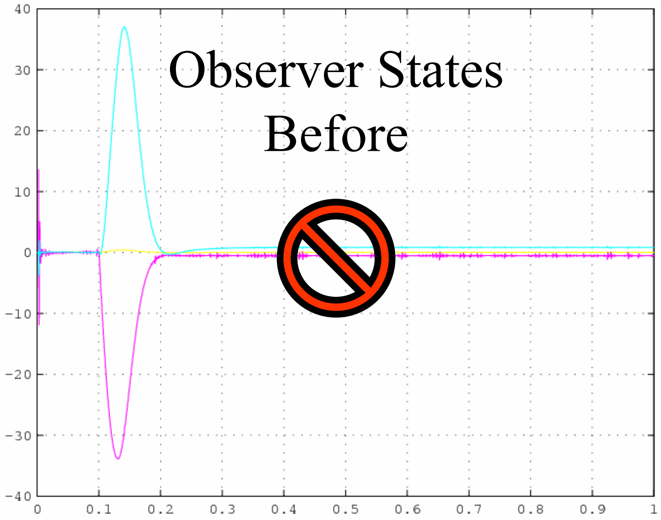
New approach:

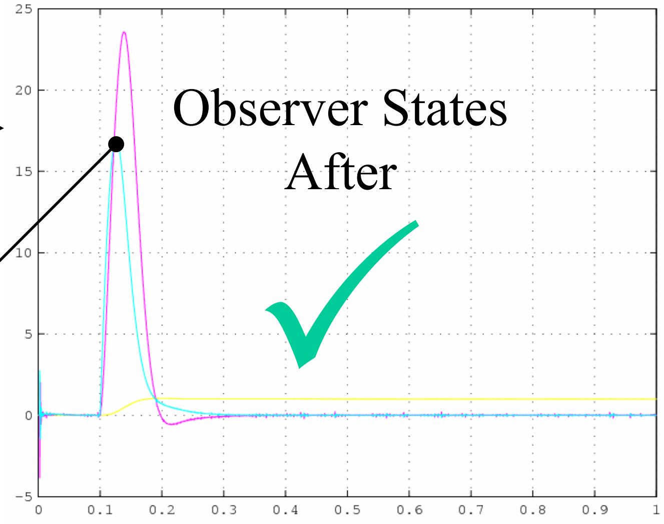
- Physics based μ-synthesis (Builds on available μ-Tools in Matlab).
- Extract reduced order controller or manually design a controller.
- Use numerical optimization (MATLAB Optimization Toolbox) to match the I/O map of the reduced controller to the full μ-controller.
- Plot compares the full μ-controller with the final one.



3.2 Before & After Physics Based µ-Synthesis

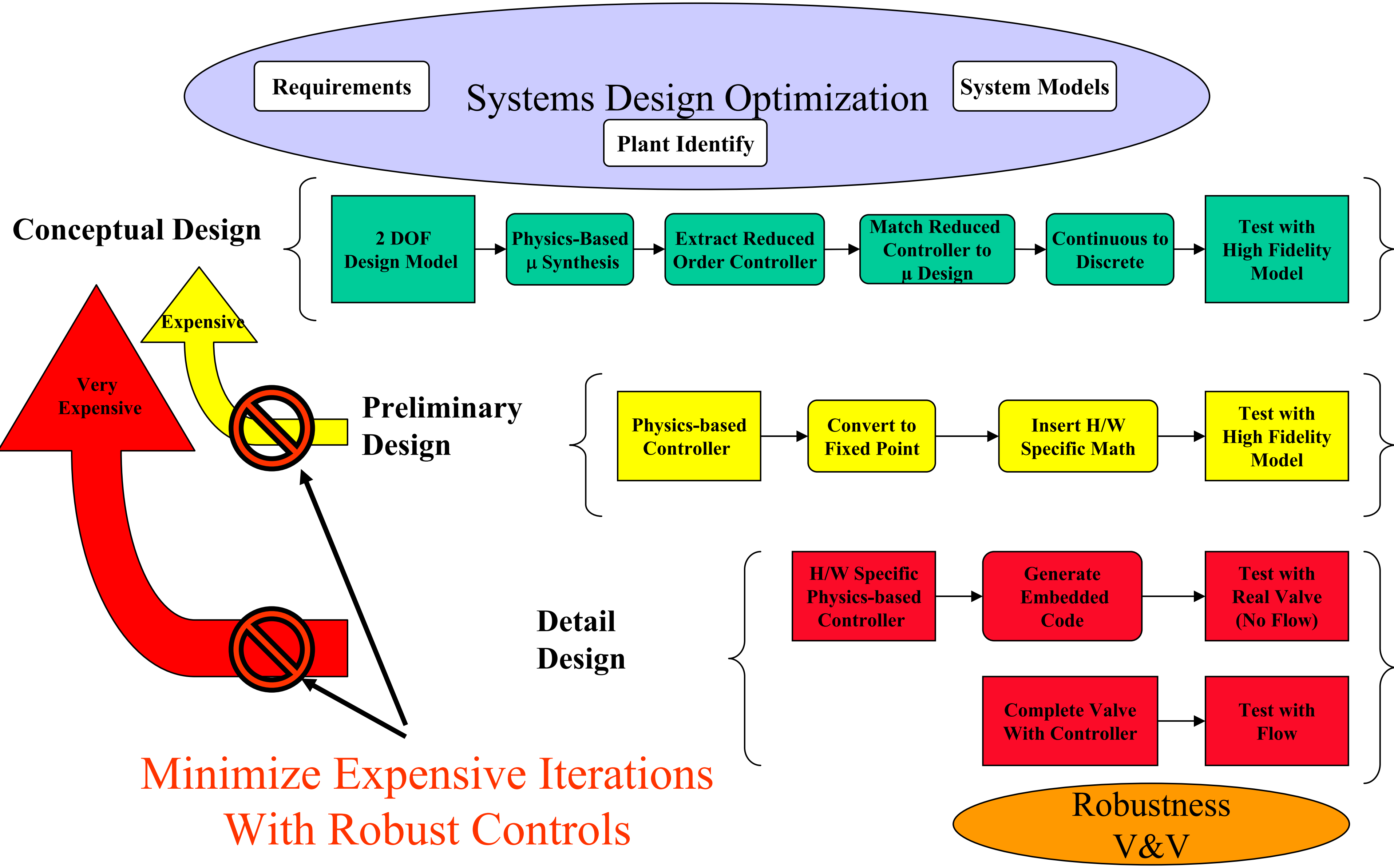






- **Physically meaningful states help detect problems:**
  - **e.g. can ask: why is this state not tracking the real plant state?**

3.3 The Design Process



Systems Design Optimization

Requirements

Plant Identify

System Models

Conceptual Design

2 DOF Design Model → **Physics-Based µ Synthesis** → **Extract Reduced Order Controller** → **Match Reduced Controller to µ Design** → **Continuous to Discrete** → **Test with High Fidelity Model**

Preliminary Design

Physics-based Controller → **Convert to Fixed Point** → **Insert H/W Specific Math** → **Test with High Fidelity Model**

Detail Design

H/W Specific Physics-based Controller → **Generate Embedded Code** → **Test with Real Valve (No Flow)**

Complete Valve With Controller → **Test with Flow**

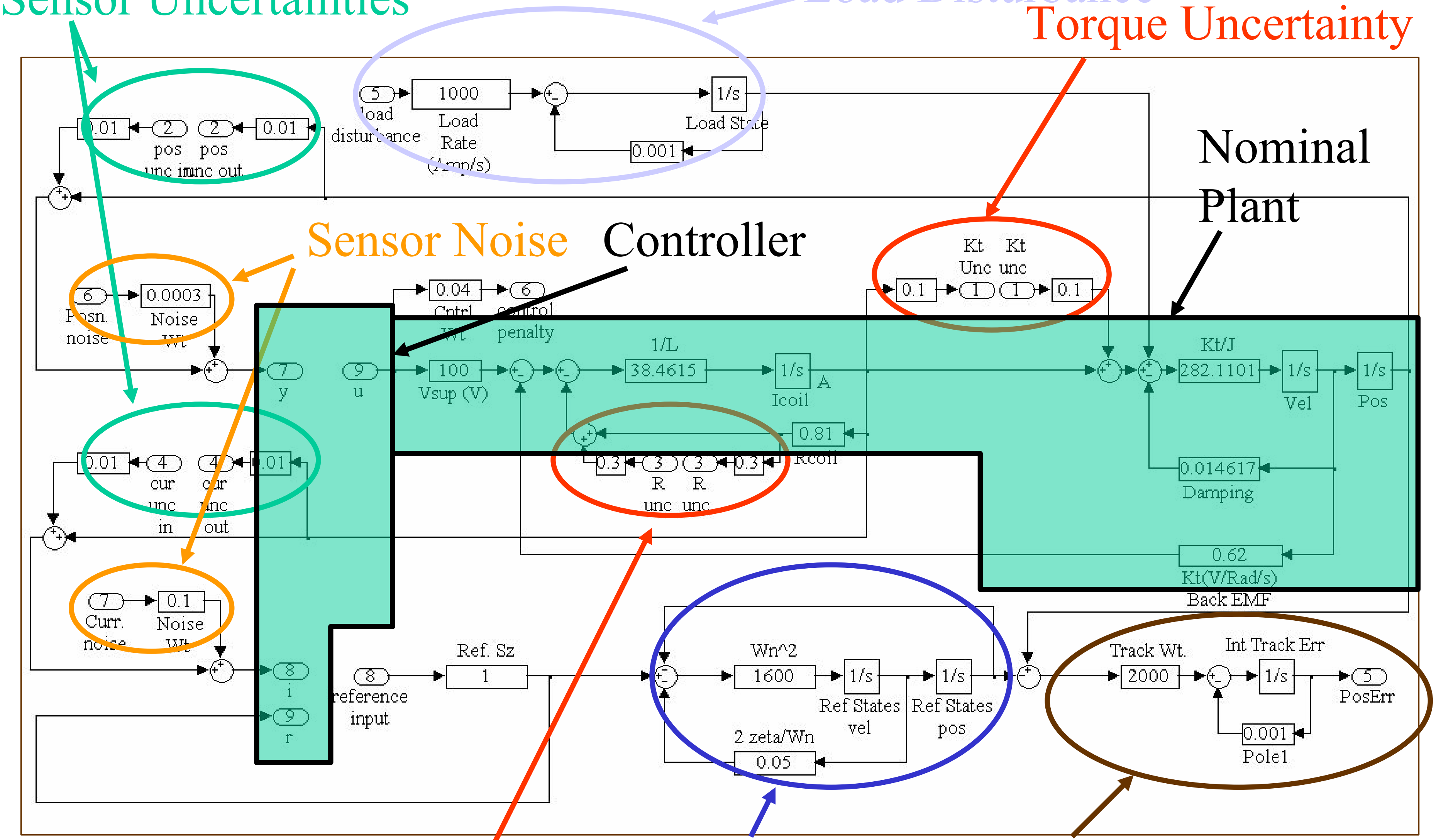
Expensive

Very Expensive

Robustness V&V

Minimize Expensive Iterations With Robust Controls

3.4 The 2-DOF Design Model in Simulink



Sensor Uncertainties

Load Disturbance

Torque Uncertainty

Nominal Plant

Sensor Noise

Controller

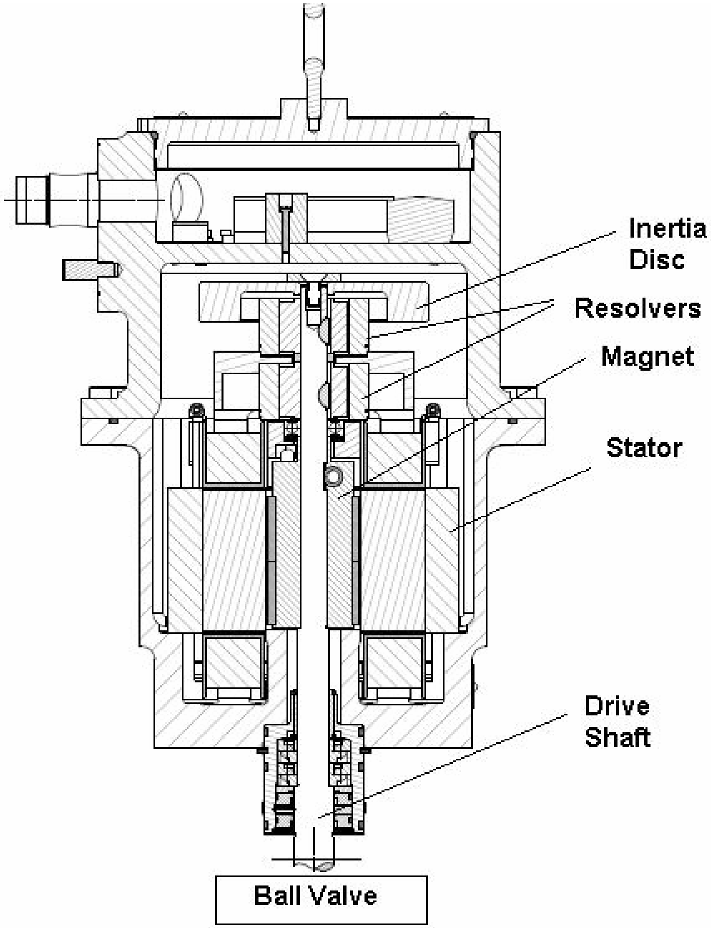
Resistance Uncertainty

Ideal Response

Tracking Requirement

4. Industrial Application to GS16 Turbine Metering System

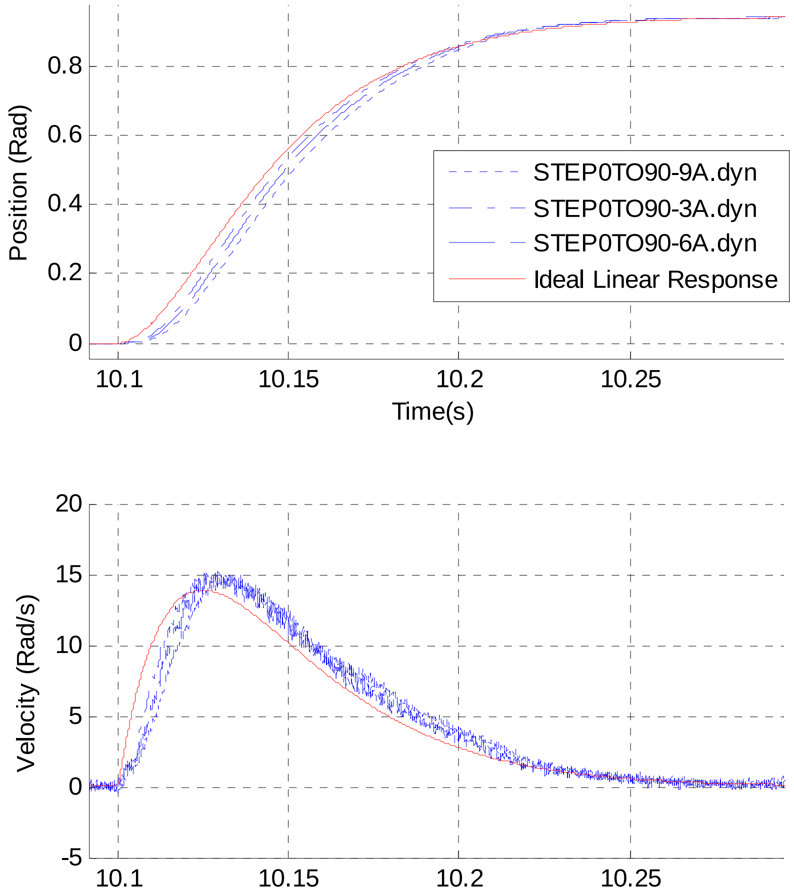
- Large nonlinear friction due to stringent turndown ratios and flow accuracy requirements.
- Stringent Performance and Stability Requirements:
  - positioning accuracy better than 0.005 %.
  - step response
    - 100 ms rise time
    - zero over/undershoot
  - frequency response
    - upper and lower bounds on magnitude and phase response
    - wide operational variations (temperature, pressure, supply voltages, flow loads, friction, command and sensor noise etc).



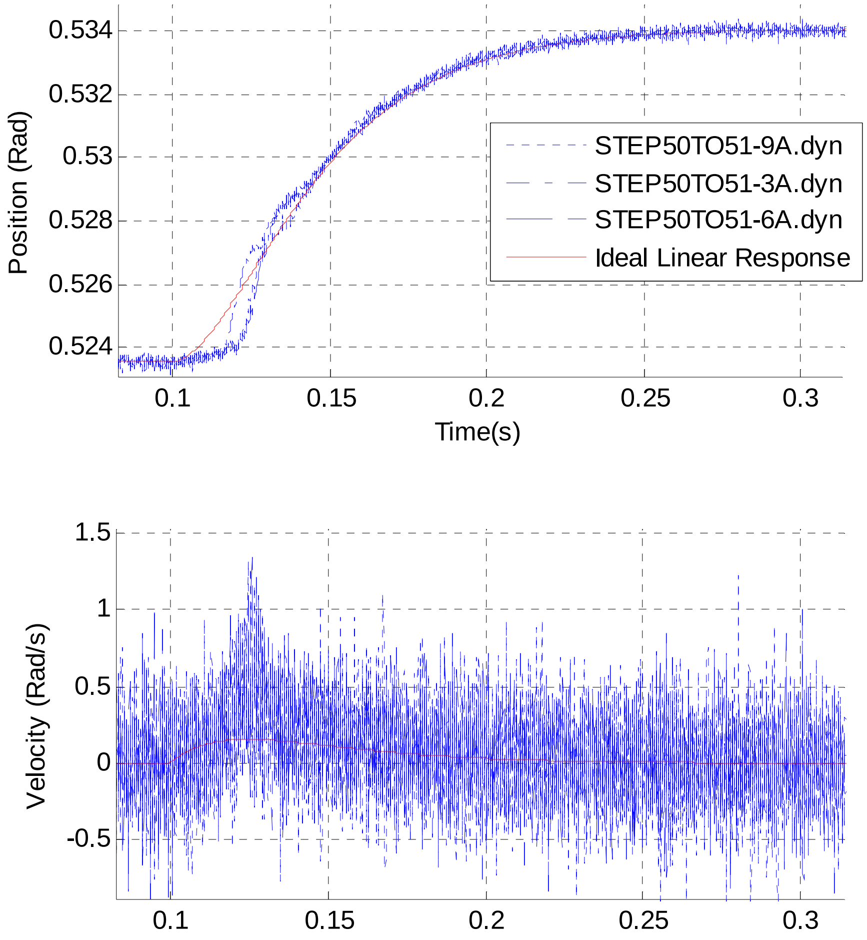
4.1 *Iteration 1* Results: Measured Robustness to Friction: Step Response

Response remained close to ideal (red curve) despite 3 fold rise in friction.

Robustness of Step Response to Dry Friction Change from 3 to 9 Amps.



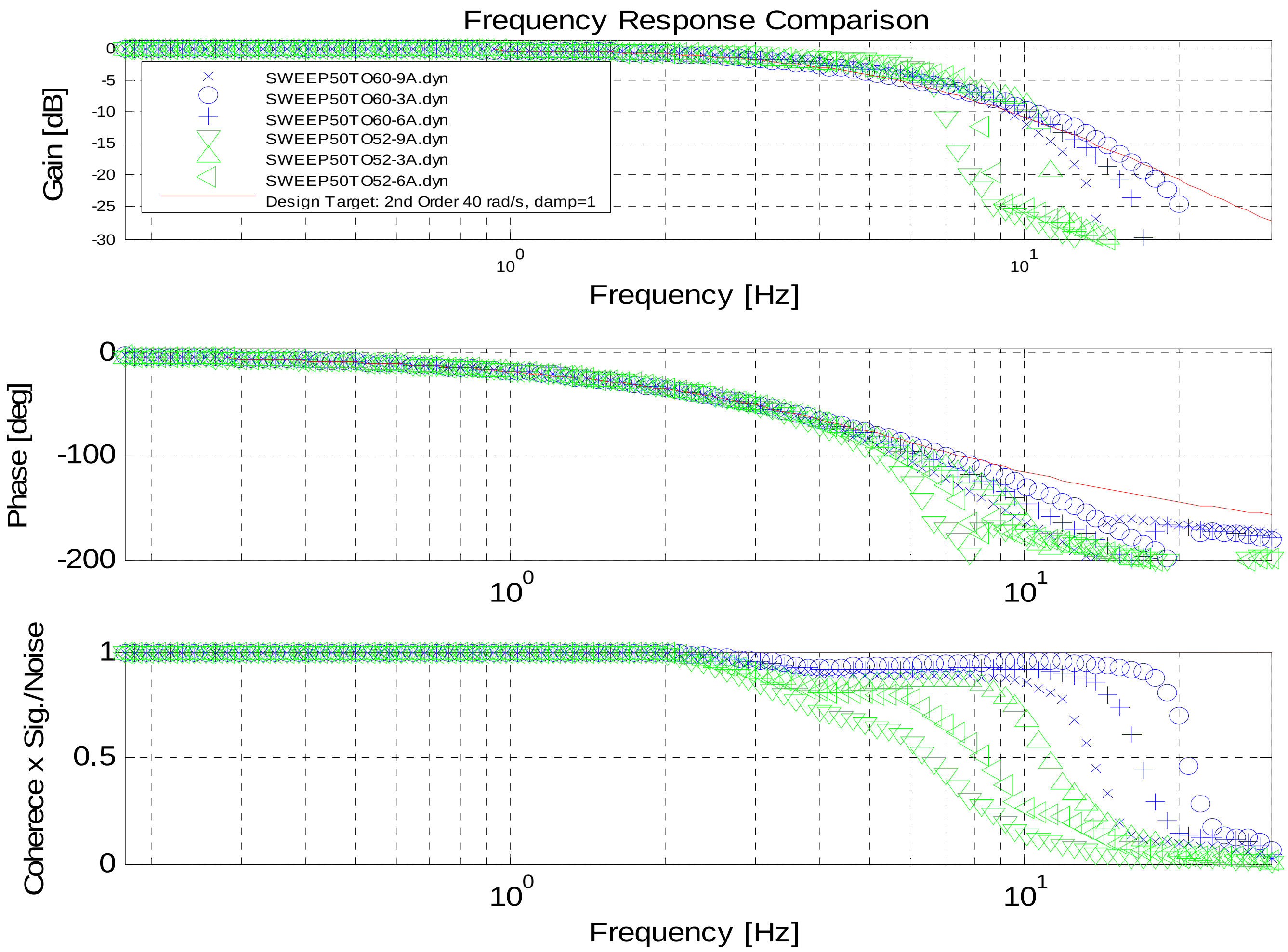
Robustness of Step Response to Dry Friction Change from 3 to 9 Amps.



4.2 *Iteration 1* Results: Measured Robustness to Friction: Frequency Response.

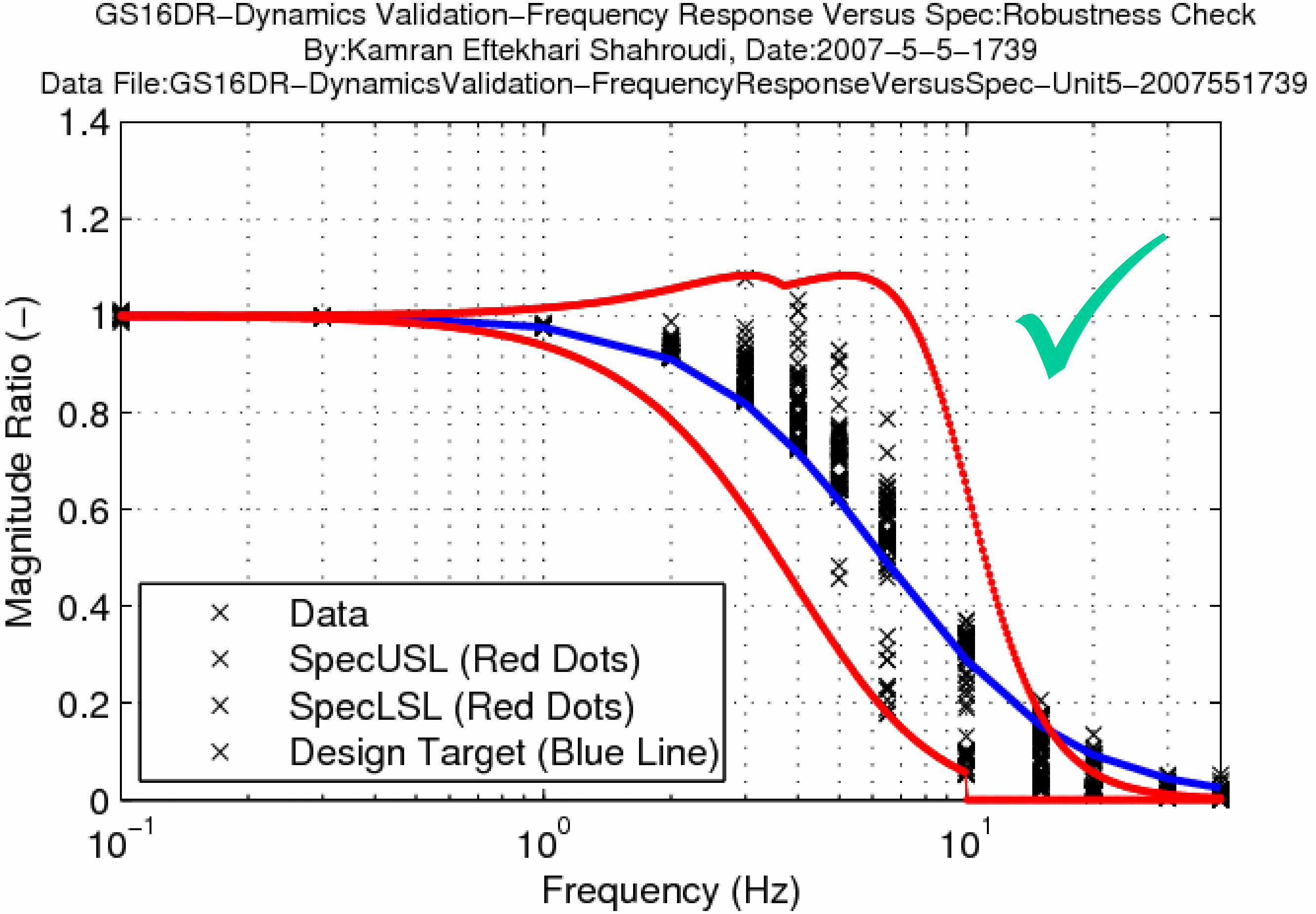
Magnitude and Phase response remained ideal up to very high frequencies:

- **despite 3 fold rise in friction!**



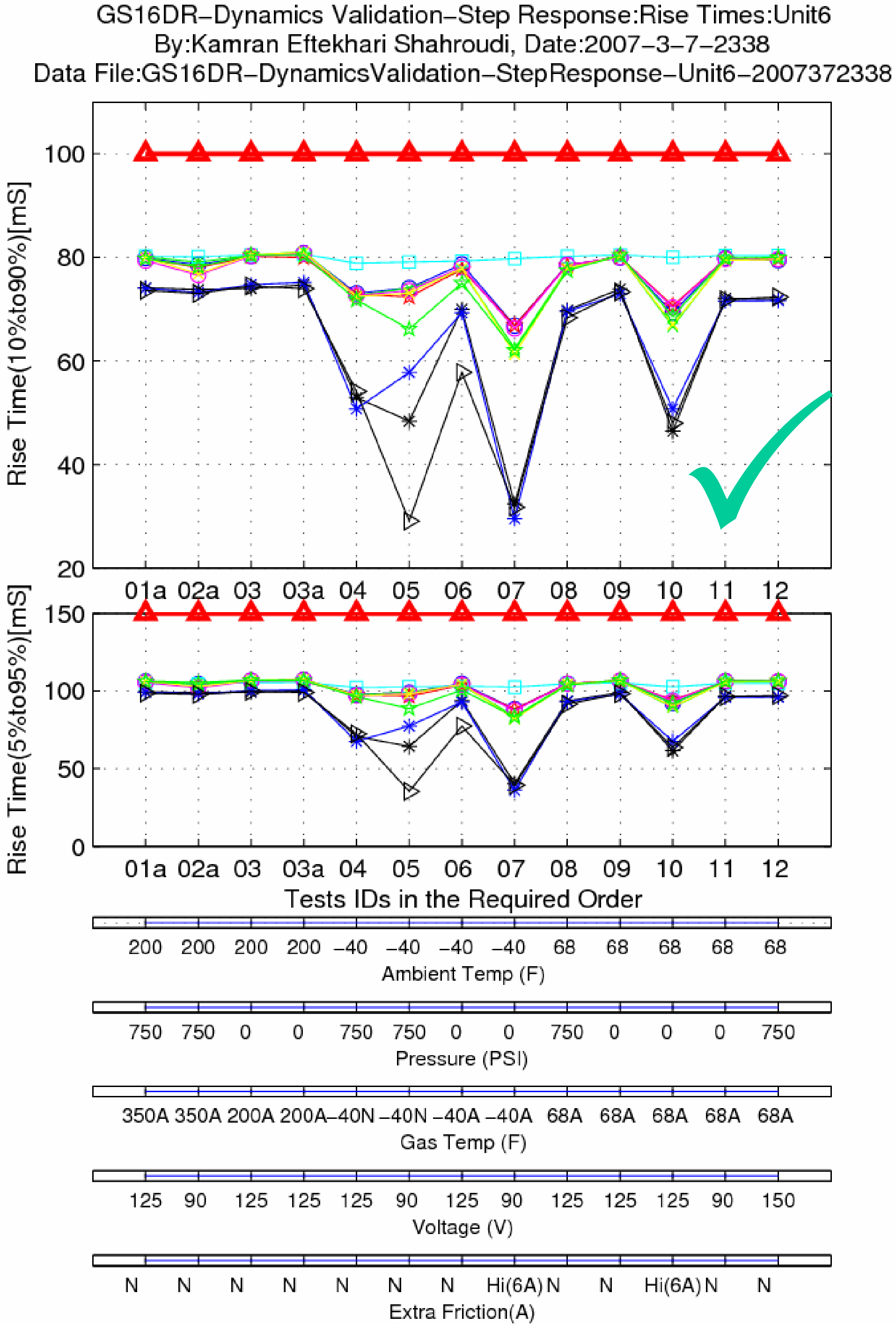
4.3 V&V : Frequency Response

- Plot compiles data from 100 tests at extreme conditions.
- The worst case performance must remain inside bounds.
- The ability to design to meet specs upfront is key!



GS16DR–Dynamics Validation–Frequency Response Versus Spec:Robustness Check
By:Kamran Eftekhari Shahroudi, Date:2007–5–5–1739
Data File:GS16DR–DynamicsValidation–FrequencyResponseVersusSpec–Unit5–2007551739

4.4 V&V: Step Response



- **Measured step responses at extreme conditions.**
- **The worst case rise time must remain below 100 ms (10% to 90% criterion).**
- **The ability to design to meet specs upfront is key!**

4.5 Practical Hurdles: These problems were not trivial !

- How to detect coding problems or design mistakes:
  - Incorrect sampling rates.
  - Finding the right balance between gains and sensor limitations.
- How to cope with design changes:
  - Multi-body dynamics issues as the shaft was extended to add a second position sensor.
  - Numerical overflow problems due to incorrect fixed point scaling.
- Physics-Based approach always helped because:
  - We could log physically meaningful observer states at run time.
  - We found the source of some problems by checking for physically impossible behavior or checking whether the observer was tracking.

4.6 Experienced Advantages of Physics-Based μ-Synthesis

- **Fast Cycle Time or Time to Market benefits since:**
  - mistakes are made faster upfront.
  - the iterative work was shifted upfront in the design process.
  - quick resolution of root cause of problems.
- **Re-use benefits (e.g. for next project) since:**
  - majority of the work was at a higher abstraction level.
- **Non-linear benefits since:**
  - the Physical meaning gave insight and handles to extend the application of a purely linear tool to a highly non-linear problem.
- **V&V Benefits since:**
  - minimized the build-test-fix cycle.
  - more robust to spec changes (e.g. bandwidth change).
  - more robust to variation in customer use profile.
- **Easier to explain the function to the rest of the development team.**

4.7 Remaining Problems

- **The relationship of design weights and D-scales to physics is not clear.**
- **Interpretation of μ-plots in terms of well understood physics are very difficult:**
  - **Try explaining to NPI team members that we need to reduce friction because μ (the infimum singular value) is too high.** Good Luck!
- **Visualization of the μ-analysis results:**
  - **Which uncertainty, noise, disturbance or plant characteristic is the main robust performance or stability driver at each frequency?**
  - **How can we trade Robust Performance and Stability?**

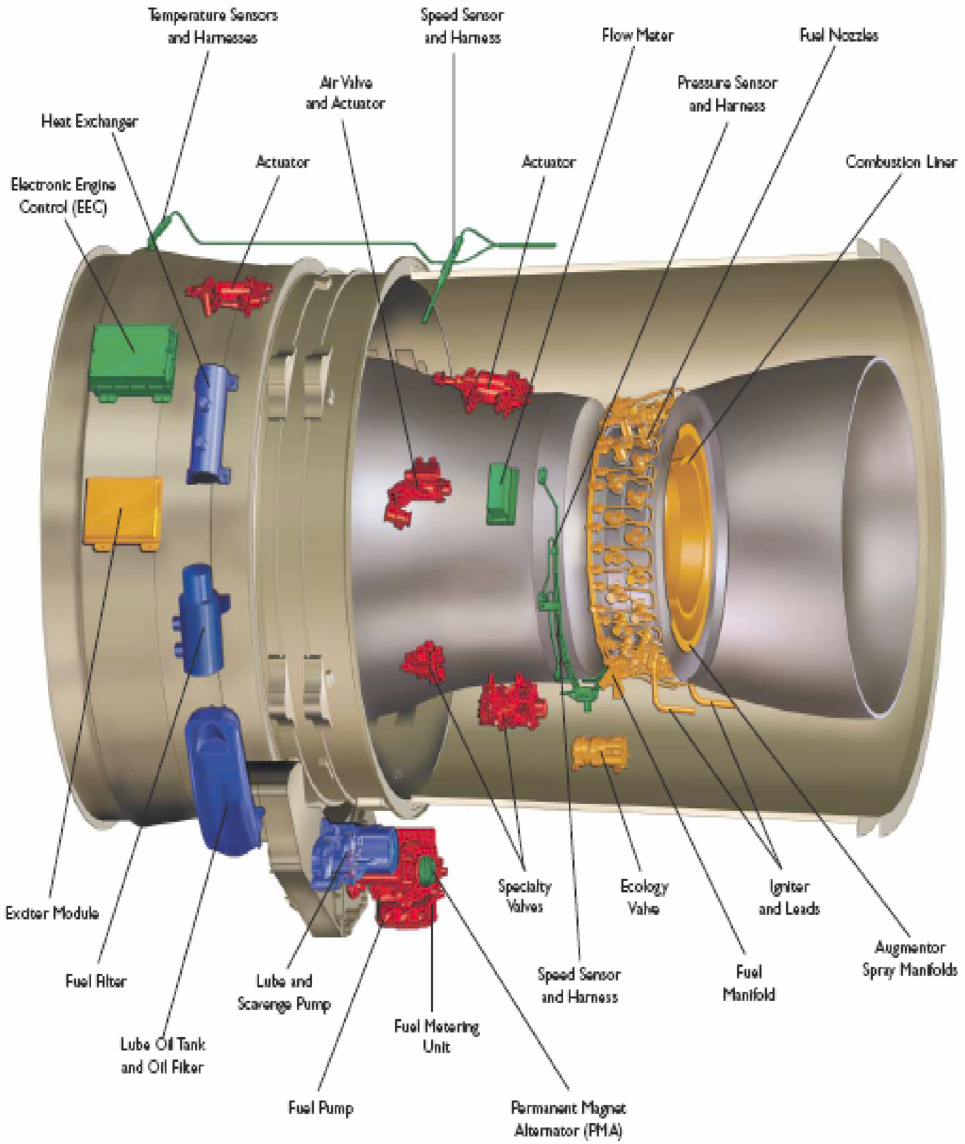
5. Recommendations for Future Tool Improvements

- **Better visualization and interpretation of μ-Synthesis results:**
  - **Show which elements (e.g. sensor quality, mechanical uncertainties etc.) are driving robust performance and stability at each frequency.**
  - **The underlying math is there but we need tools to better interpret the results.**
  - **Link to 6 σ terminology.**
- **Develop tools to enable purely physics driven μ-Synthesis process:**
  - **Physics of Design Weights and States**
  - **Meaning of D-Scales.**
  - **Useful decomposition.**
  - **Approximately retaining physical meaning after reduction.**
- **For more information please read:**
  - **Paper by K E Shahroudi in IEEE TCST 2006, vol. 14, no6, pp. 1097-1104.**
  - **Presentation by the same authors at ACC 2007 Conference in New York this summer.**

Conclusions

- We have measured unprecedented robust performance and stability in a very tough industrial controls application.
- We built a Physics-Based Robust Controller Synthesis Process on top of existing Matlab Toolboxes (μ-Tools, Optimization and Simulink).
- Robust Design Philosophy is infusing many large OEM's (such as GE) but the difficulty is:
  - How to generate robust designs upfront by synthesis rather than build-test-fix cycles.
  - How to relate their normal robustness measures to metrics they already understand (e.g. Six Sigma terminology).
- We believe these approaches can shine for highly complex MIMO type problems elsewhere.
- We identified some key directions for improving the Robust Controls Synthesis tools.

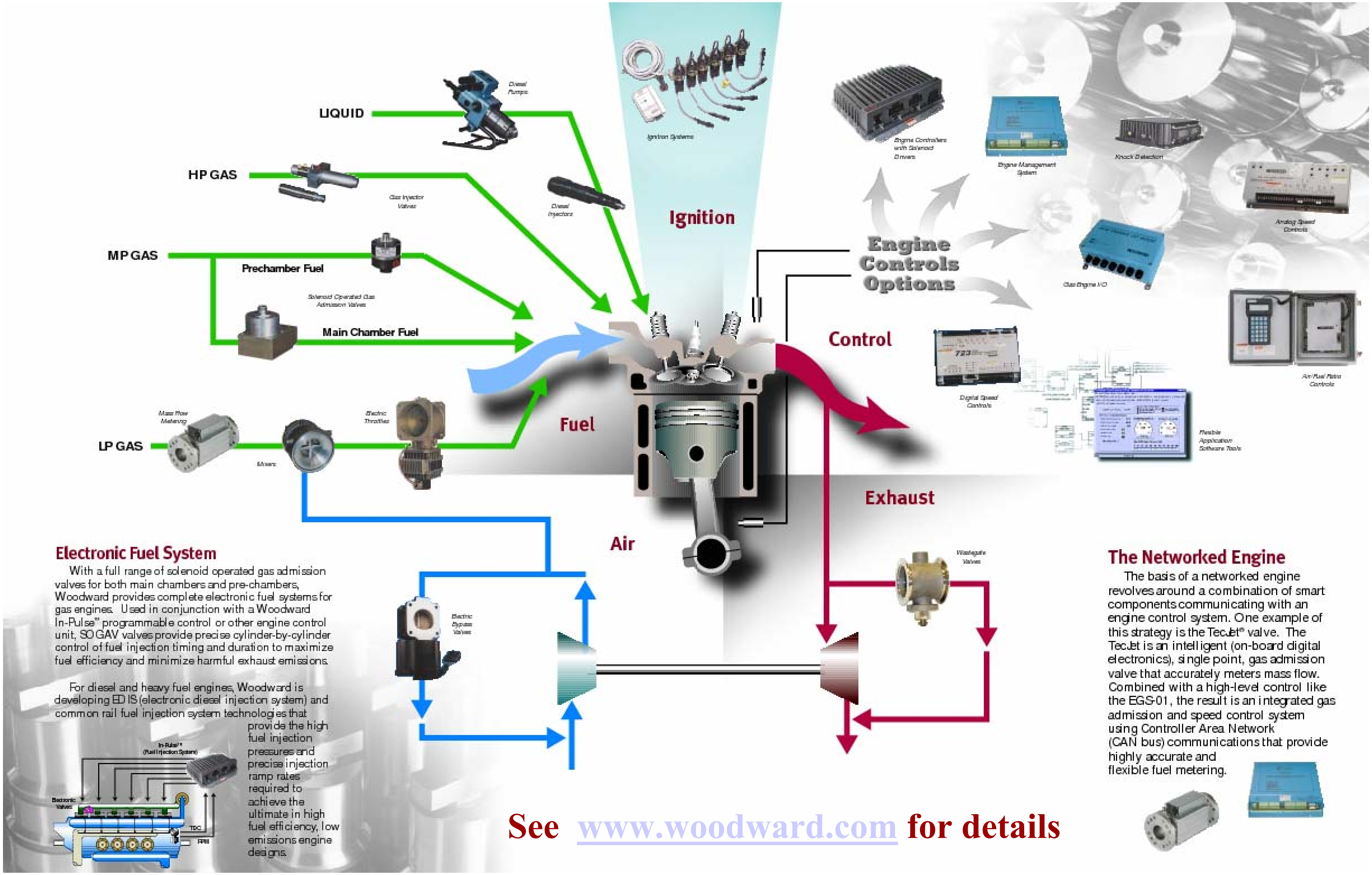
6.1 Integrated Energy Control and Optimization Solutions from Woodward: Aircraft Engine



- Systems Integration
- Fuel Systems
  - Fuel Metering, Pump, Actuation, Air Valves, Specialty Valves.
- Combustion System
  - Fuel Injection, Ignition, Manifolds, Sensors.
- Heat Management
  - Heat Exchangers, Lube and Scavenge Pumps, Filtration System, Fuel/Oil Sensors.
- Electrical System
  - Electronic Control, Sensor Suite and Power Systems.

See www.woodward.com for details

6.2 Integrated Energy Control and Optimization Solutions from Woodward: Reciprocating Engine



Electronic Fuel System

With a full range of solenoid operated gas admission valves for both main chambers and pre-chambers, Woodward provides complete electronic fuel systems for gas engines. Used in conjunction with a Woodward In-Pulse™ programmable control or other engine control unit, SOGAV valves provide precise cylinder-by-cylinder control of fuel injection timing and duration to maximize fuel efficiency and minimize harmful exhaust emissions.

For diesel and heavy fuel engines, Woodward is developing EDIS (electronic diesel injection system) and common rail fuel injection system technologies that provide the high fuel injection pressures and precise injection ramp rates required to achieve the ultimate in high fuel efficiency, low emissions engine designs.

The Networked Engine

The basis of a networked engine revolves around a combination of smart components communicating with an engine control system. One example of this strategy is the TecJet® valve. The TecJet is an intelligent (on-board digital electronics), single point, gas admission valve that accurately meters mass flow. Combined with a high-level control like the EGS-01, the result is an integrated gas admission and speed control system using Controller Area Network (CAN bus) communications that provide highly accurate and flexible fuel metering.

See www.woodward.com for details