Temperature Control of Diffusion/CVD Furnaces Using Robust Multivariable Loop-Shaping Techniques

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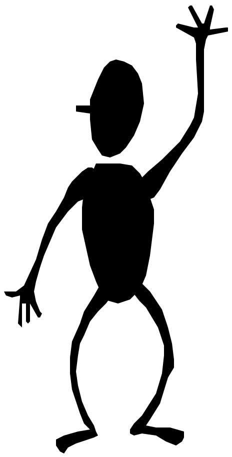
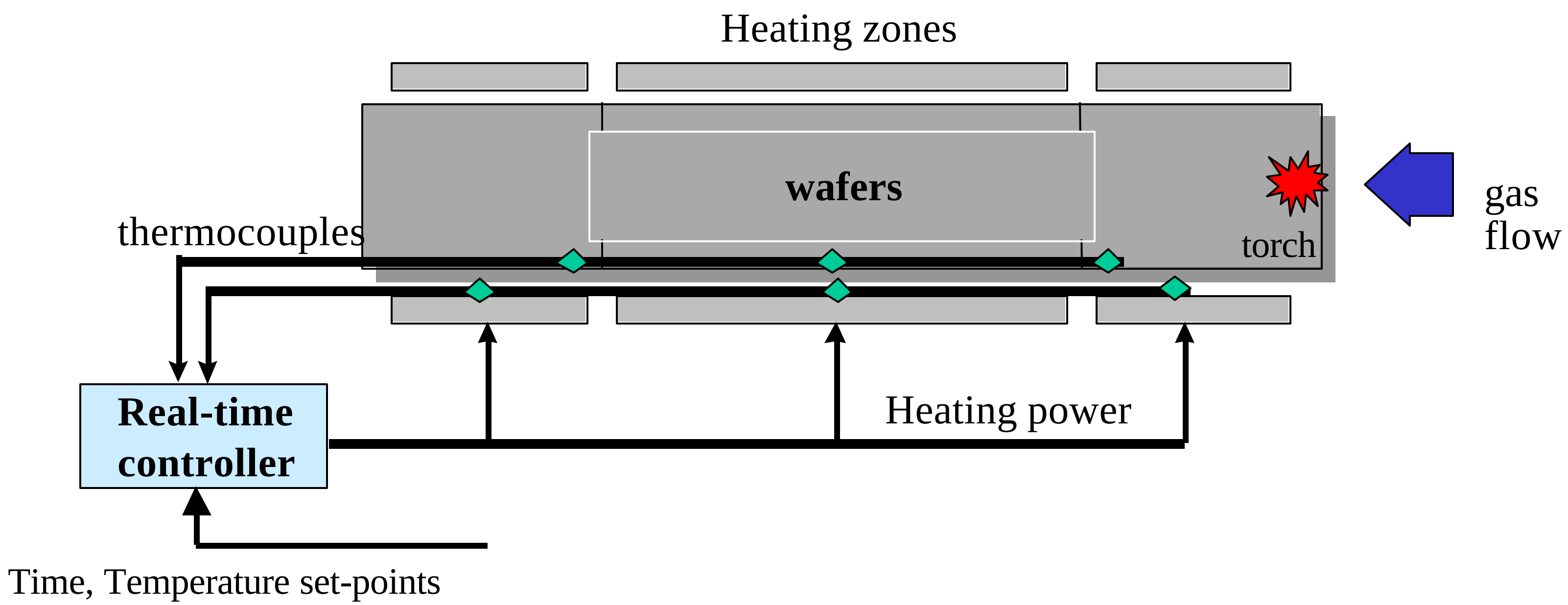


- Issues:
  - Tight temperature control
  - Quick design turnaround (for retrofitting apps)

Introduction I

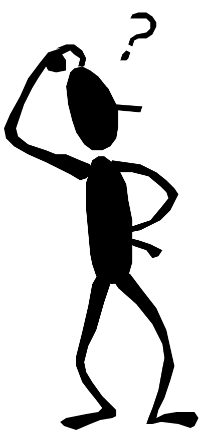


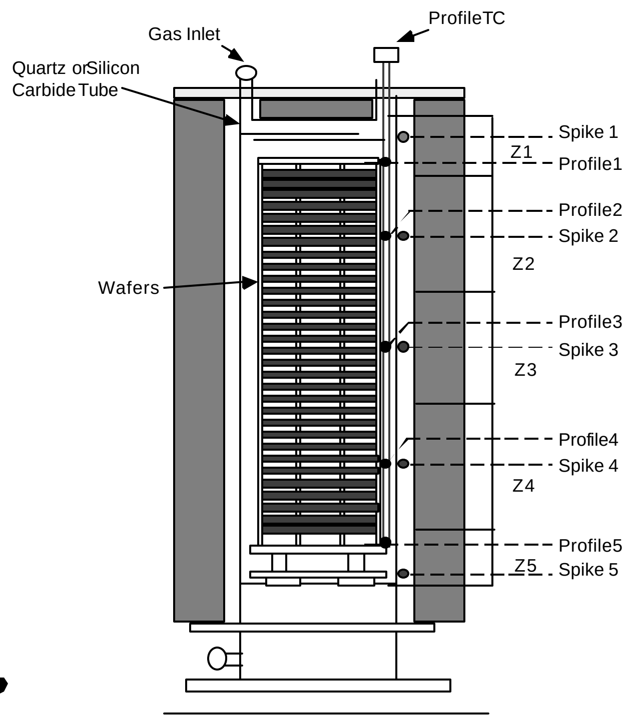
- Temperature uniformity, fast stabilization, disturbance attenuation,...
- Quick design, minimal iterations (furnace down-time)
- Low expertise requirements

Introduction II

- Standard Practice:
  - Spike PID, Profile table look-up
  - Periodic Profiling, Disturbances, Stabilization, Uniformity

- Model-based multivariable control
  - Modeling (nominal+uncertainty)
  - Controller design (loop-shaping)
  - Implementation
  - Multiple operating points





Modeling I

- System Identification
- Control-Oriented ID: Uncertainty description compatible with the controller design method.
  - Our choice: Loop-Shaping (available insight, computations) based on sensitivity and complementary sensitivity targets.
  - Nominal Model: MISO equation error, yielding a linear estimation model

$$y = N(\theta)[u] + D(\theta)[y] + e = w^T\theta$$

  - Estimated parameters include initial conditions; this is important to handle short input-output sets that begin on a transient.
  - Continuous time model.
  - Regularization of estimates

Modeling II

- Coprime Factor Description of the Uncertainty
- Robust Stability Condition: $\sigma\, [C\ S\ D^{-1}]\ \sigma\, [\Delta_N] + \sigma\, [S\ D^{-1}]\ \sigma\, [\Delta_D] < 1$
- $CS \sim P^{-1}T$: Relates uncertainty to target loop properties (controller independent).
- Uncertainty estimate + Target selection: Minimize RSC
- Effective closed loop uncertainty estimate: (for outer loop design)

$$\delta_{M,e} < \{\sigma\, [\, S\ D^{-1}\,]\ \sigma\, [\, C\ S\,]\ \sigma\, [\, T^{-1}\,]\ \sigma\, [\Delta_N] + \sigma\, [S\ D^{-1}\,]\ \sigma\, [\Delta_D]\ \}\ \alpha$$

$$\alpha = (1 - \sigma\, [C\ S\ D^{-1}]\ \sigma\, [\Delta_N] + \sigma\, [S\ D^{-1}\,]\ \sigma\, [\Delta_D]\,)^{-1}$$

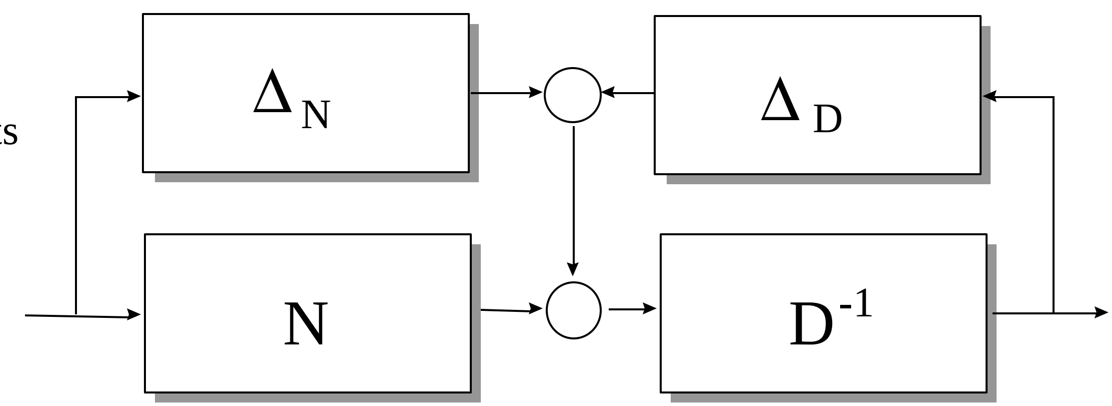
Interpretation:

Δ_N => compl. sensitivity constraints

(high frequencies)

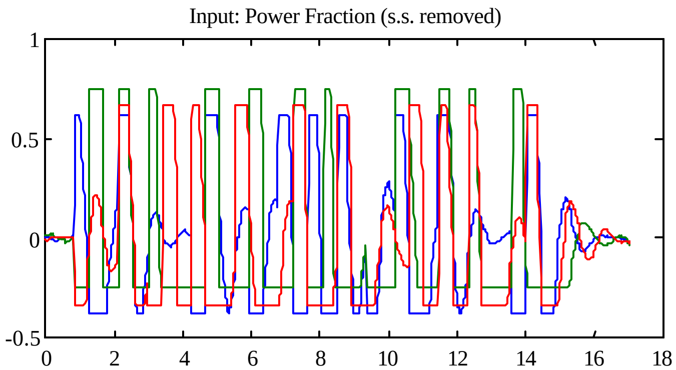
Δ_D => sensitivity constraints

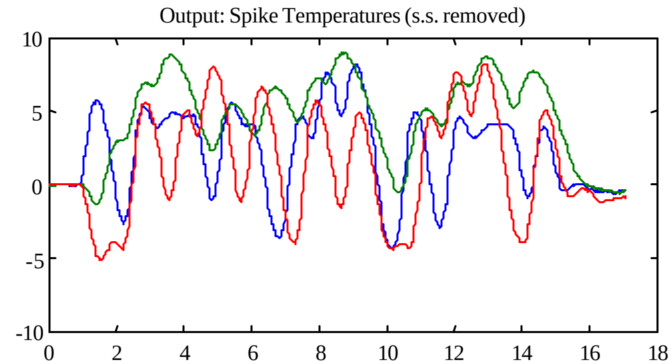
(low frequencies)

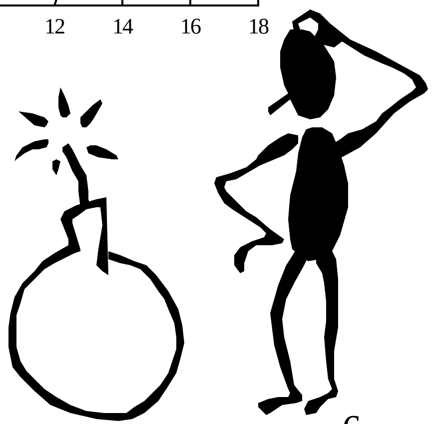


Modeling III

- Identification Experiment:
  - ~20 min test (net time at the operating conditions)
  - Target bandwidth ~5 rad/min

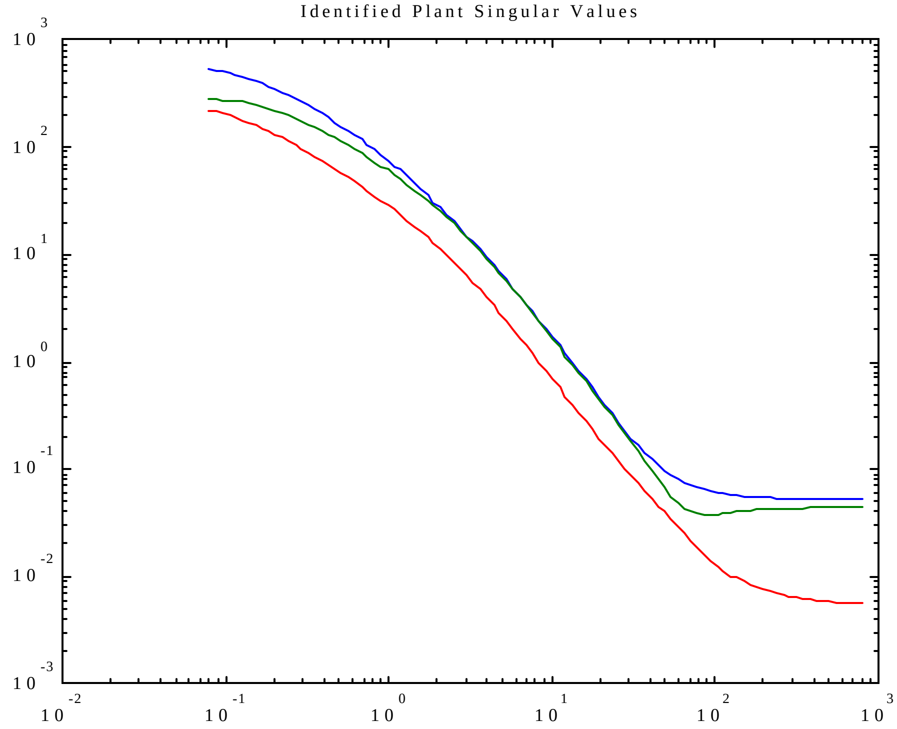


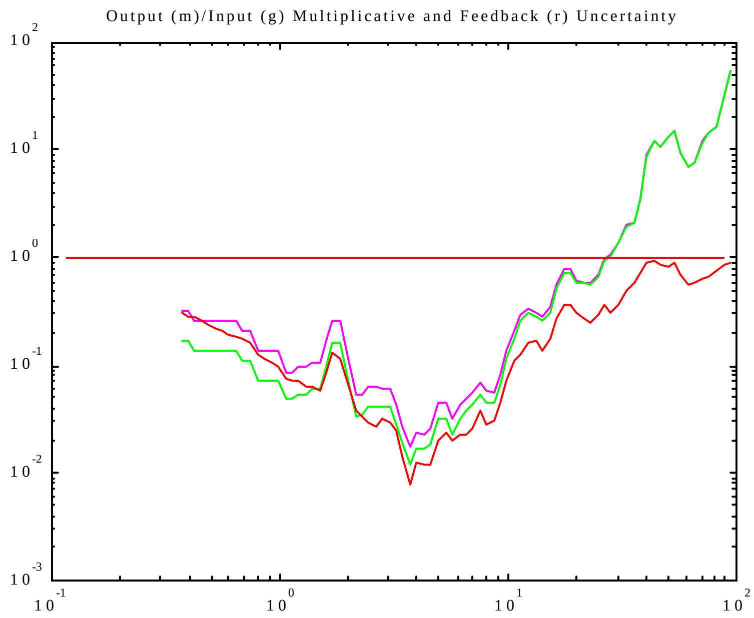




Inner Loop (Spike Subsystem) Modeling

- Power to spike temperature. Very high and uncertain low frequency gain. (but good model around the intended crossover)

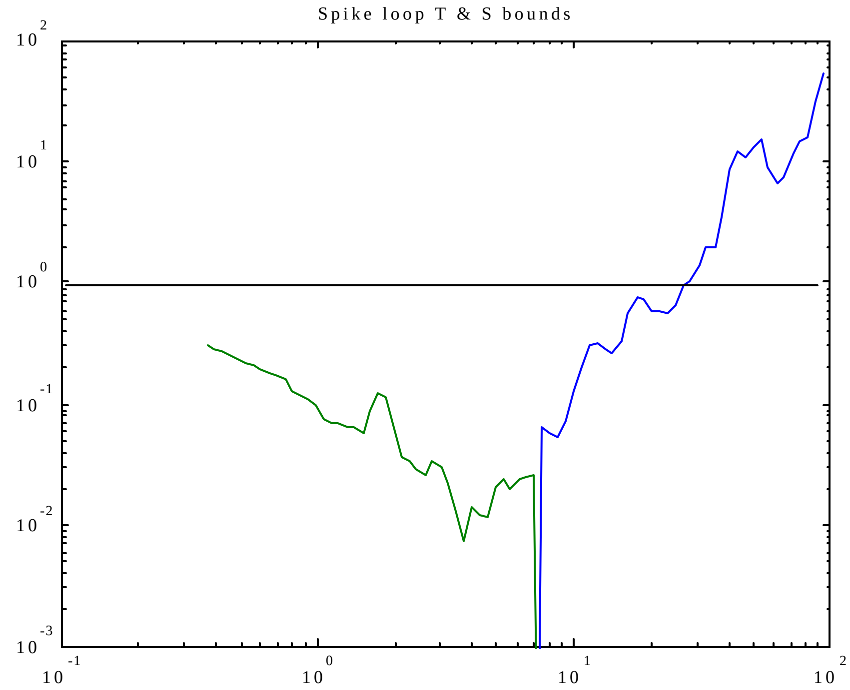


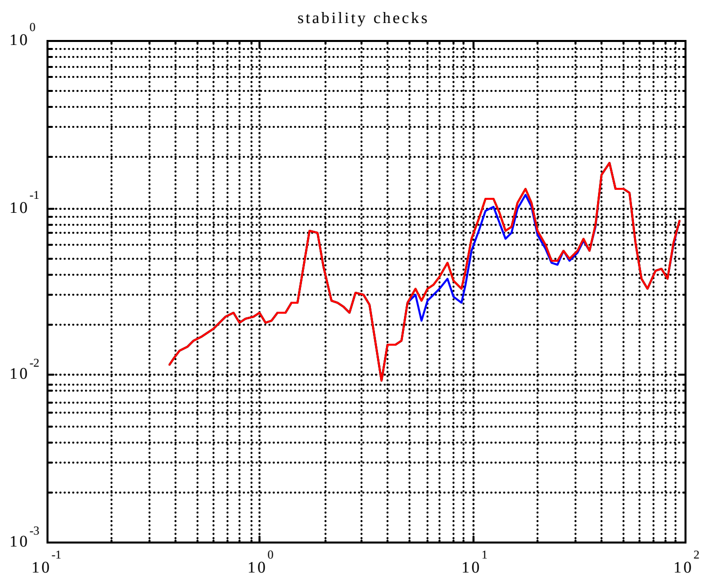


- “Raw” uncertainty data expressed as inverse S&T bounds (|fft(e)|/|fft(u)|, |fft(e)|/|fft(y)|) show asymptotic behavior.

Spike Model Uncertainty

- After the split, the high frequency uncertainty is expressed as an inverse T constraint and the low frequency as an inverse S constraint.

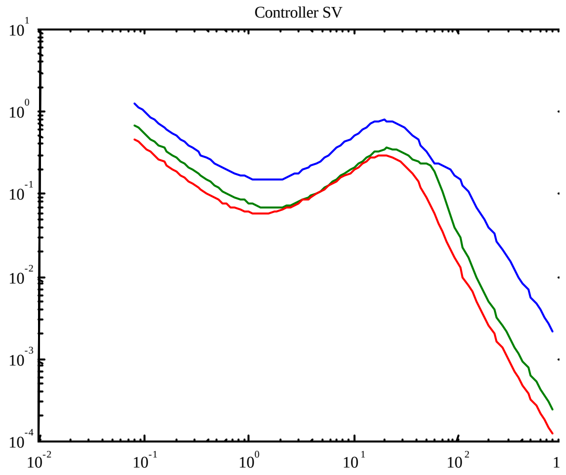


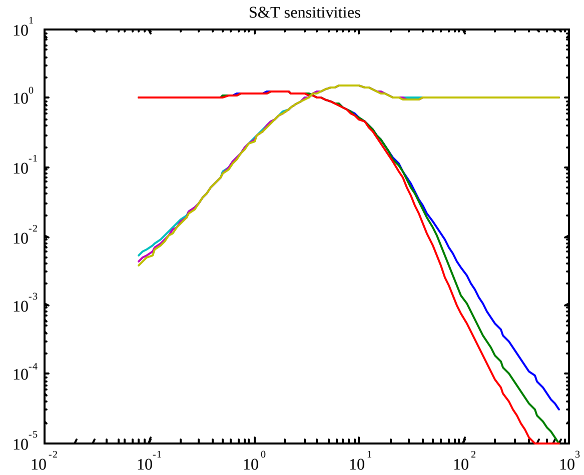


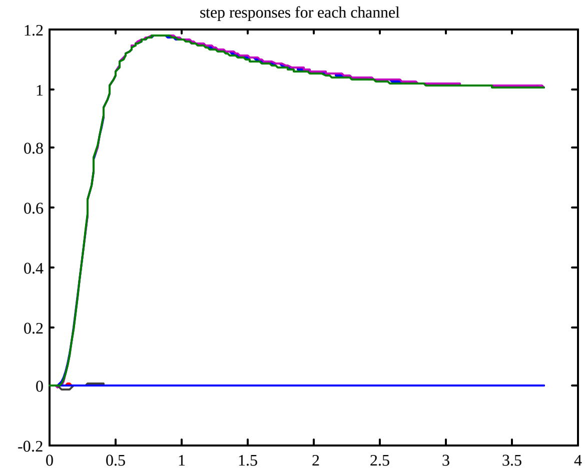
- Rare limitations from RHP zeros
- Small RSC => Confidence in the design

Spike Controller Design

- Target loop => weighted H-infinity sensitivity optimization
- The approach yields excellent matching properties with minimal iterations in the weight selection.
- Simple weights => Automation, Low expertise requirements.

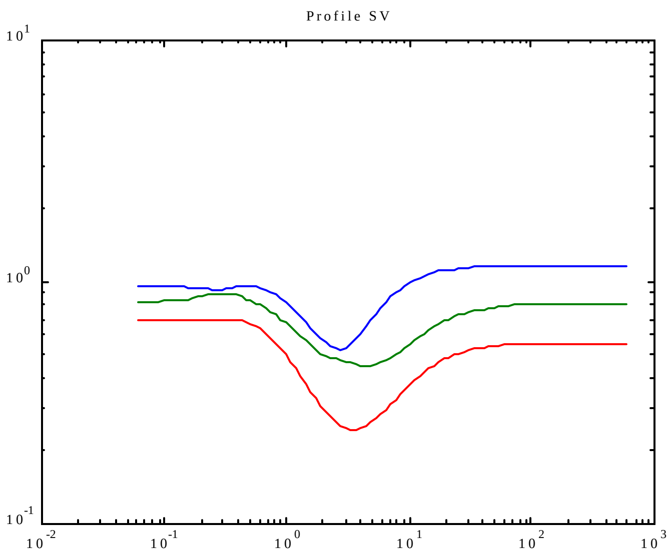


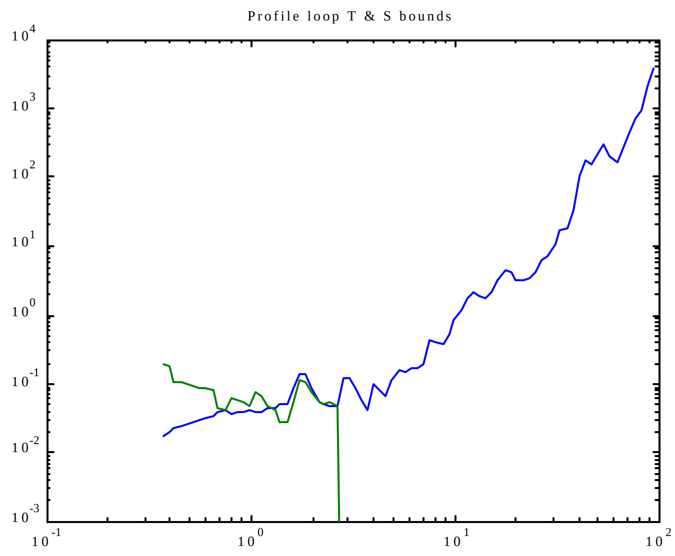




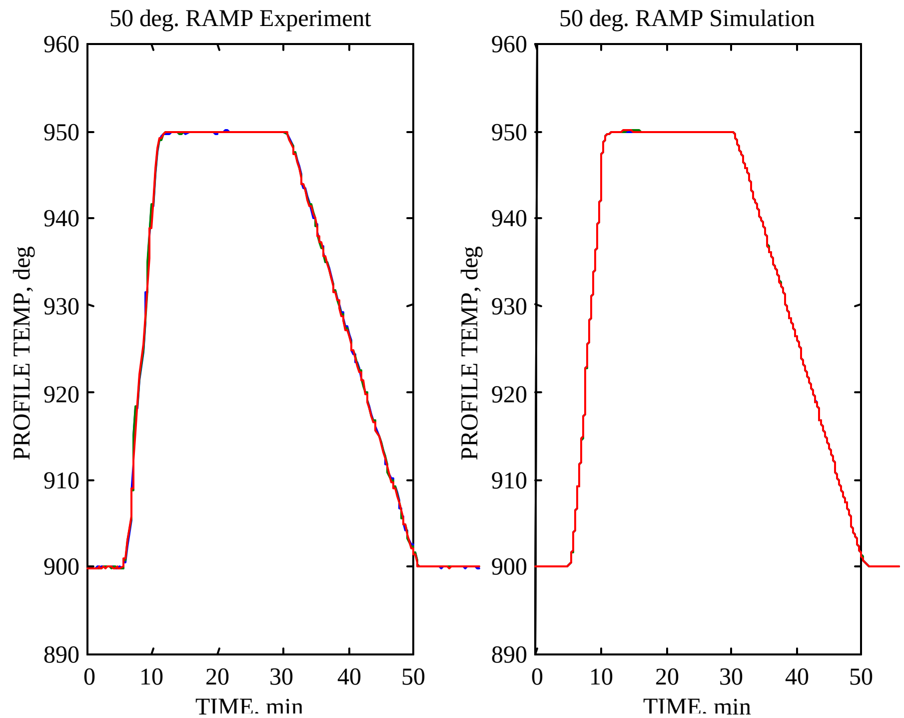
Outer Loop (Profile Subsystem)

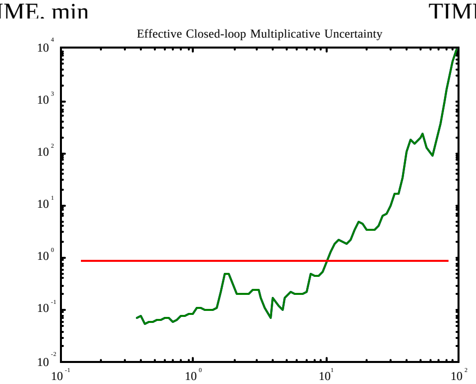
- The profile subsystem (spike to profile temperatures) is identified in a similar manner.
- Target loop constraints: profile subsystem uncertainty, nominal inner closed-loop, effective inner closed-loop uncertainty.
- The profile controller is designed for the combined profile/inner-loop system. Typically a straightforward design.





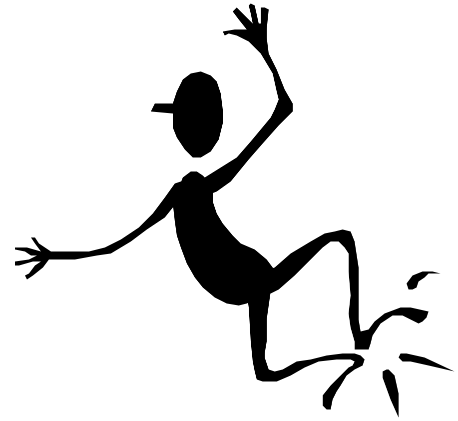
Controller Implementation and Testing





- After reduction, the controller is discretized and augmented with anti-windup mechanisms.
- Excellent and predictable performance in the typical ramp-up/ramp-down operations

More Results



- "Temperature no longer variable of concern"

Source: M. Yelverton, et. al. , AEC/APC XI, 1999. (AMD)

- Process Results:
  - Decreased cycle time (faster controlled ramps, faster stabilization). Time-to-process reduced by as much as 50%
  - Increased process indices (Cp, Cpk by as much as 250%)
  - Increased tool utilization (no need for profiling)

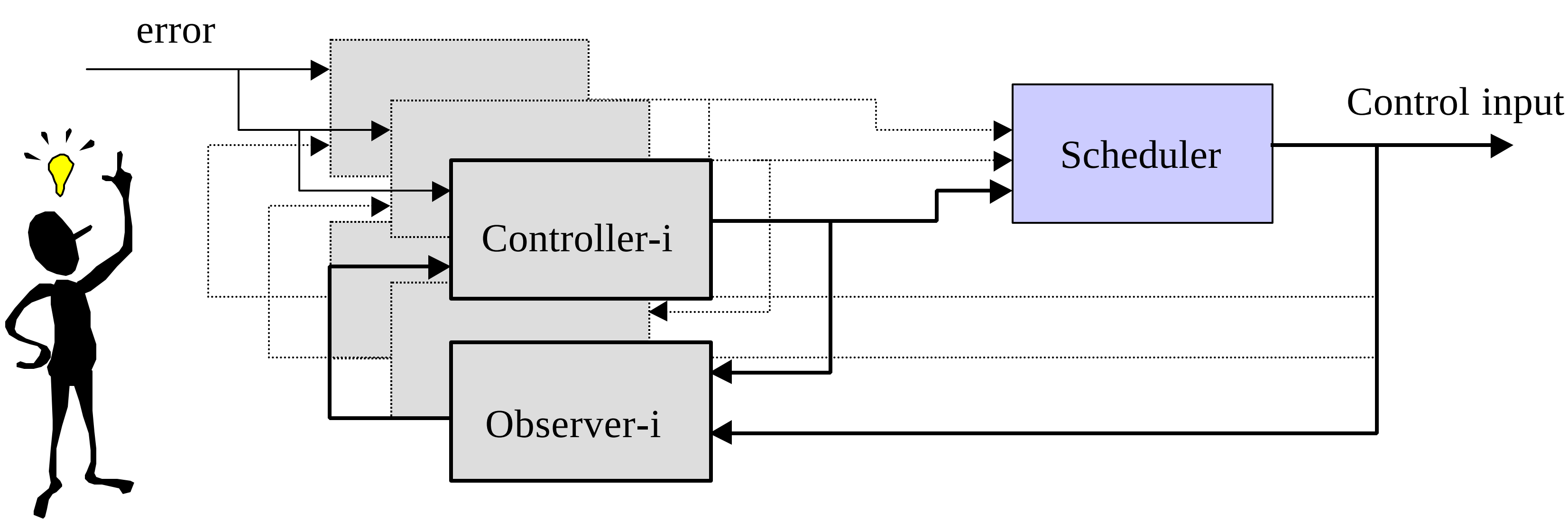
Source: Tucker, Valdez, Tsakalis, Warren and Stoddard, AEC/APC X, 1988. (Motorola, Mesa)

- >300 controllers in operation

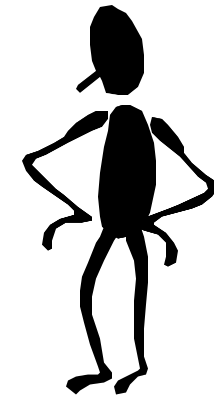
- Semiconductor Intl, Best Product Award, 1988

Controller Scheduling

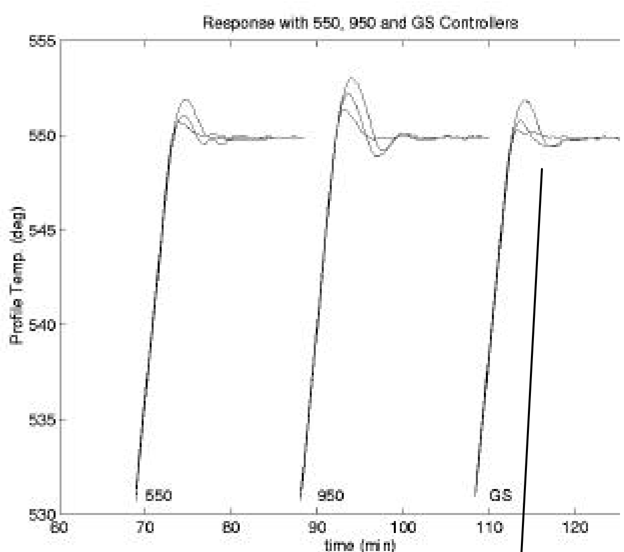
- Handling multiple operating conditions
- Modeling and controller design at different steady-states
- Scheduling with bumpless transfer techniques
  - In general, models and controllers will have different order; simple interpolation is not enough.

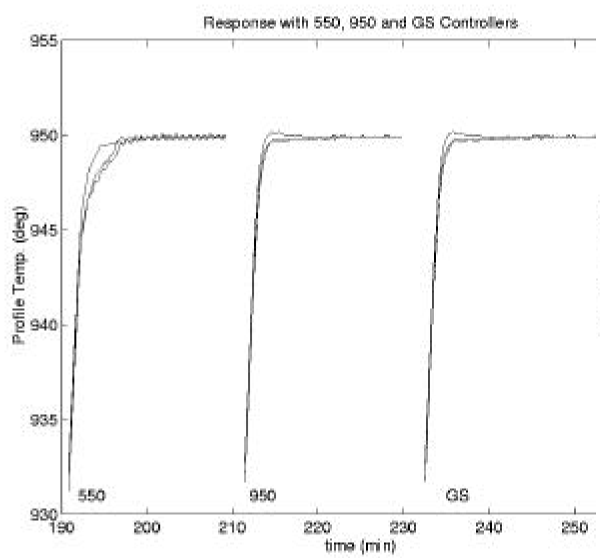


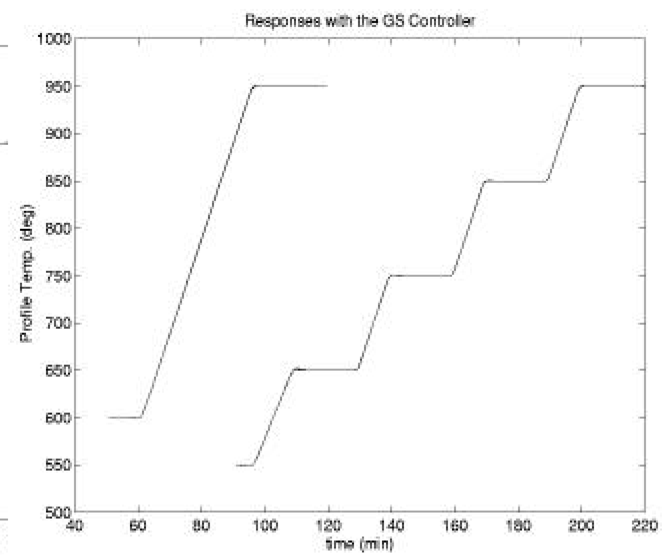
Scheduled Controller Tests



- Higher -but manageable- complexity
  - 3 controllers covering the range 500-1000 deg.C
- Scheduled controller has good performance in the entire range and transfers are fairly smooth







Overshoot due to saturation

Concluding Remarks

- Integrated method to design high-performance temperature controllers
- Quick and reliable designs; low expertise requirements
- Excellent success record
- Controller scheduling to handle wide-range operations
- Future work:
  - Tech-transfer to other processes
  - Nonlinear modeling and uncertainty descriptions