Control Methods for Temperature Control of Heated Plates

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Problem Overview/Motivation

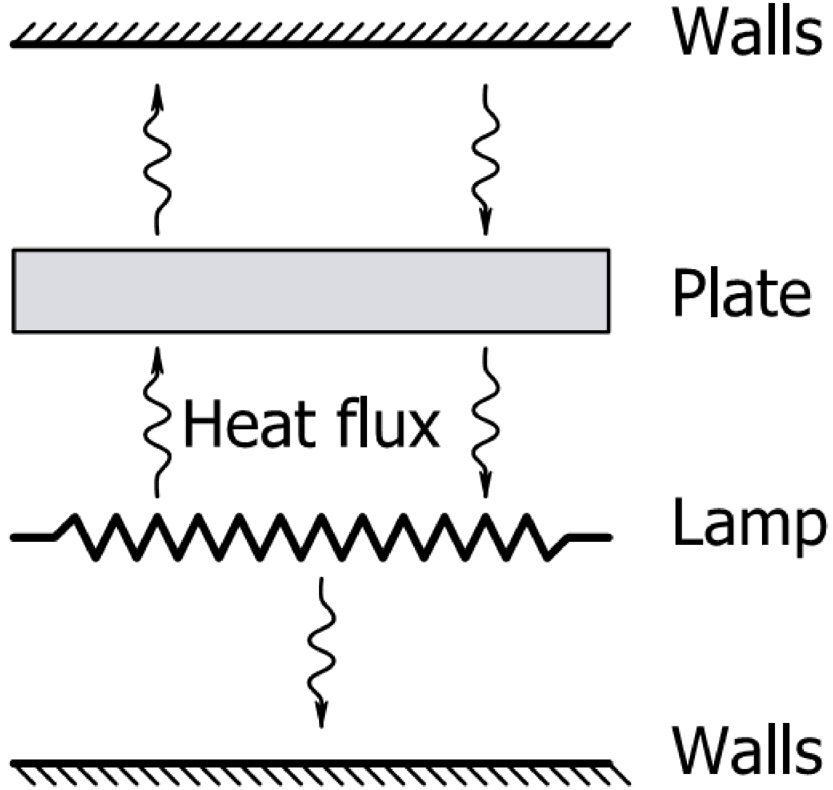
- Temperature control is important in many thermal processing systems
- The dynamic response of the system can change considerably depending on operating temperature, wafer types, and/or process conditions
- Ideally one would like to get the exact same closed-loop temperature response *(performance)* despite these system variations *(robustness)*
- Here we use a simple example to compare three different control approaches in terms of their performance and robustness

Overview

- Thermal Model of Lamp Heated Plates
- Process Variations and Robust Control
- Gain-Scheduled PID Control
- Linear-Quadratic-Gaussian (LQG) Control
- Model-Based Control
- Performance Comparison
- Summary

Thermal Model of Heated Plate

- A tungsten-halogen lamp is shown heating a plate from below
- The plate radiates, conducts, and convects heat to the walls and surroundings.
- The system can be divided into a number of control volumes and the heat equation can be written for the net rate of temperature change:



$$\dot{T} = f(T, u),$$
Dynamic System of Equations

$$y = g(T),$$
Sensed Temperature

For each control volume, i

$$m_i(T)\dot{T}_i = Q_i^r(T) + Q_i^c(T) + Q_i^v(T) + b_i u,$$

Thermal mass — Radiation — Conduction — Convection — Electrical Power In

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- **The heat loss from the plate to the surroundings**

$$q_s = \epsilon\sigma(T_s^4 - T_\infty^4) + h(T_s - T_\infty),$$

Effective emissivity

Effective heat transfer coefficient

Effective emissivity for infinite parallel surfaces

$$\epsilon = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}.$$

Surface 1

Surface 2

We will look at control performance when these two parameters (ε and *h*) vary.

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- ❑ Thermal Modeling of Lamp Heated Plates
- ❑ **Process Variations and Robust Control**
- ❑ Constant Gain PID Control
- ❑ Gain-Scheduled PID Control
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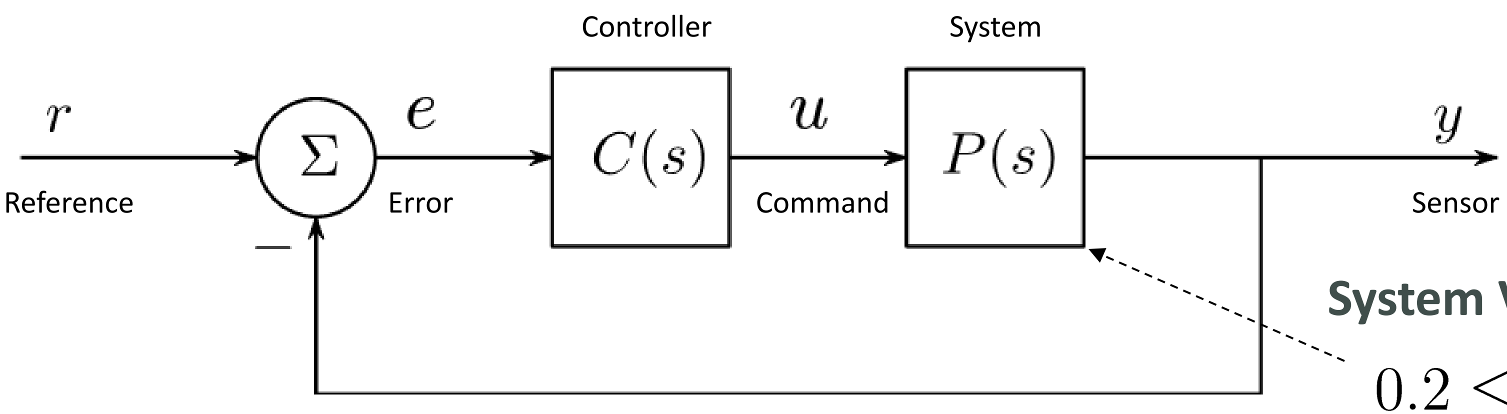
- ❑ Performance Comparison
- ❑ Summary

Process Variations and Robust Control

- Plate emissivity can change in ways that are difficult to predict
- Changes in gas flows or gas chemistry can change the heat losses
- Changes can be “wafer-to-wafer” or during processing (dynamic).
- If you knew how the losses changed, you could tune the controller for a specific process condition.
- But often you cannot know about changes so the controller must be robust
- Robustness here is defined as good performance for a wide range of process conditions.

Process Variations and Robust Control

- The feedback controller is assumed to have no prior knowledge of these variations in the plant



System Variations:

$$0.2 \leq \epsilon \leq 0.8$$
$$5 \leq h \leq 100$$

Heat loss from plate to surroundings:

$$q_s = \epsilon\sigma(T_s^4 - T_\infty^4) + h(T_s - T_\infty),$$

Effective emissivity

Effective heat transfer coefficient

- **Three control strategies:**
  - ***Gain-Scheduled PID***
  - ***Linear-Quadratic-Gaussian (LQG)***
  - ***Model-based Control (MBC)***

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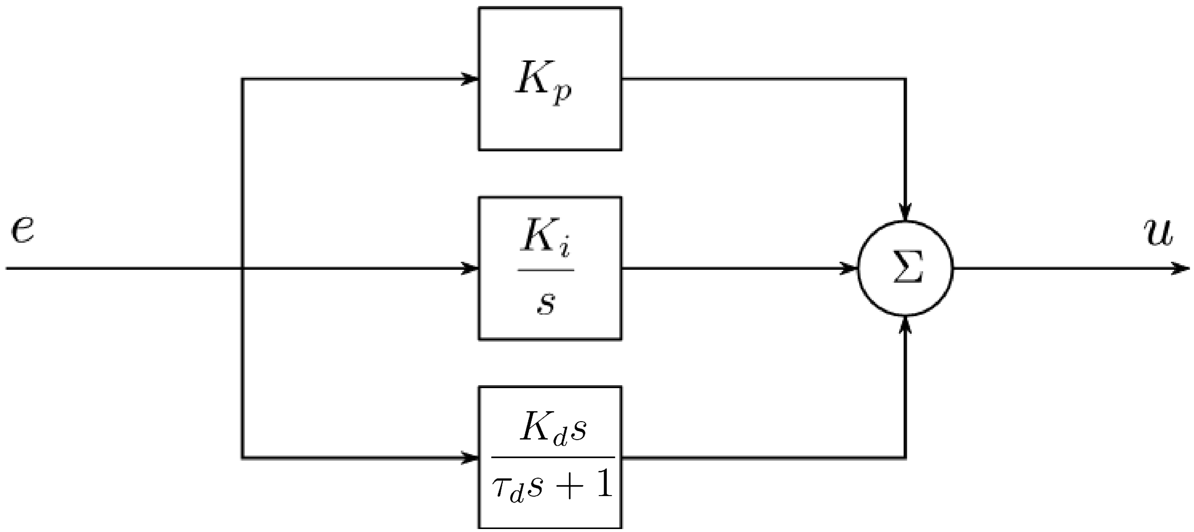
Gain-Scheduled PID Control

Proportional Gain

Integral Gain

Derivative Gain

$$C(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{\tau_d s + 1},$$

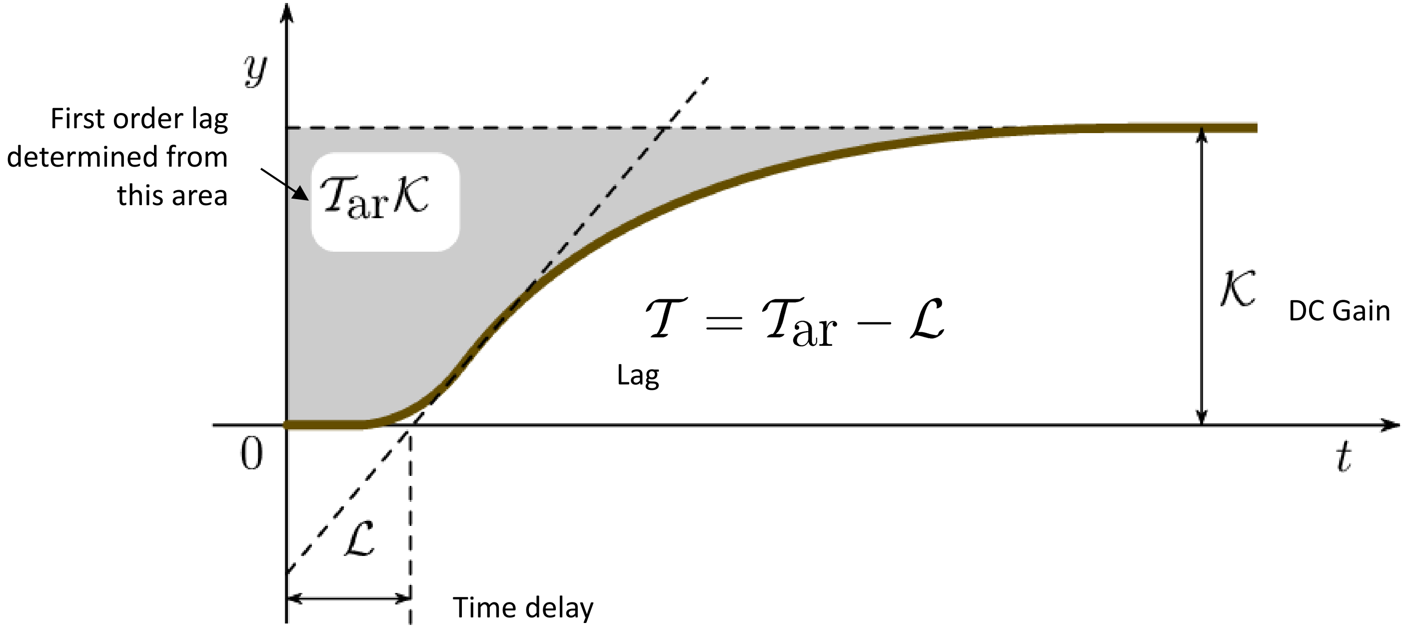


G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*, 6th ed. Prentice-Hall, 2010.

- Many strategies have been developed for selecting gains for PID
- We use the "AMIGO" method where the system is assumed to be a First Order system plus a Time Delay (FOTD).

[5] K. J. Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*, 2nd ed. Research Triangle Park, NC, USA: Instrument Society of America, 2006.

[6] ——, *Advanced PID Control*. Research Triangle Park, NC, USA: ISA - Instrumentation, Systems, and Automation Society, 2006.



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Dynamic System Variation

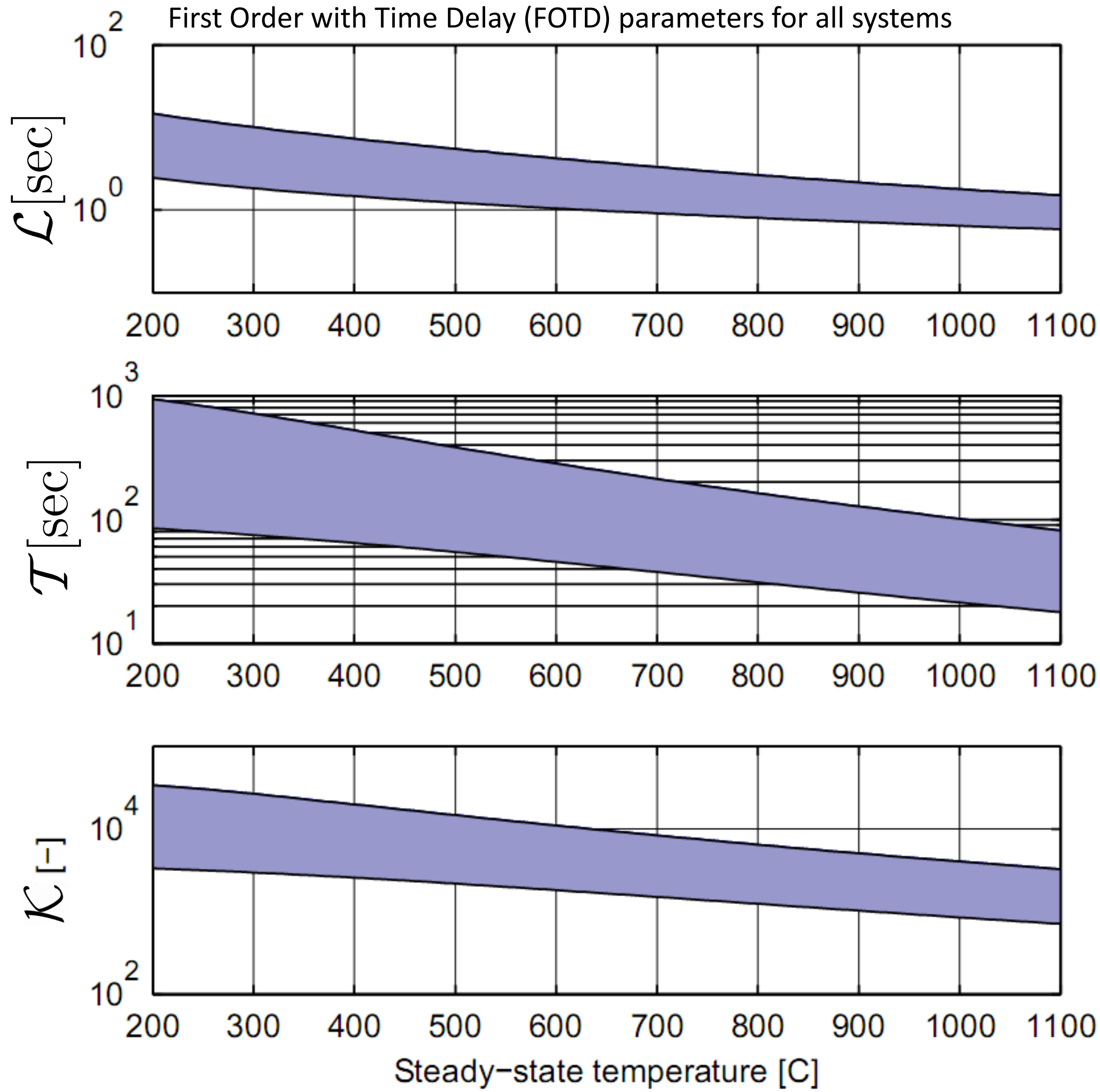
System Variations

$$0.2 \le \epsilon \le 0.8$$
$$5 \le h \le 100$$

Delay Time

First order lag time

DC Gain



System is inherently faster with smaller DC gain at higher temperature due to non-linear radiant cooling.

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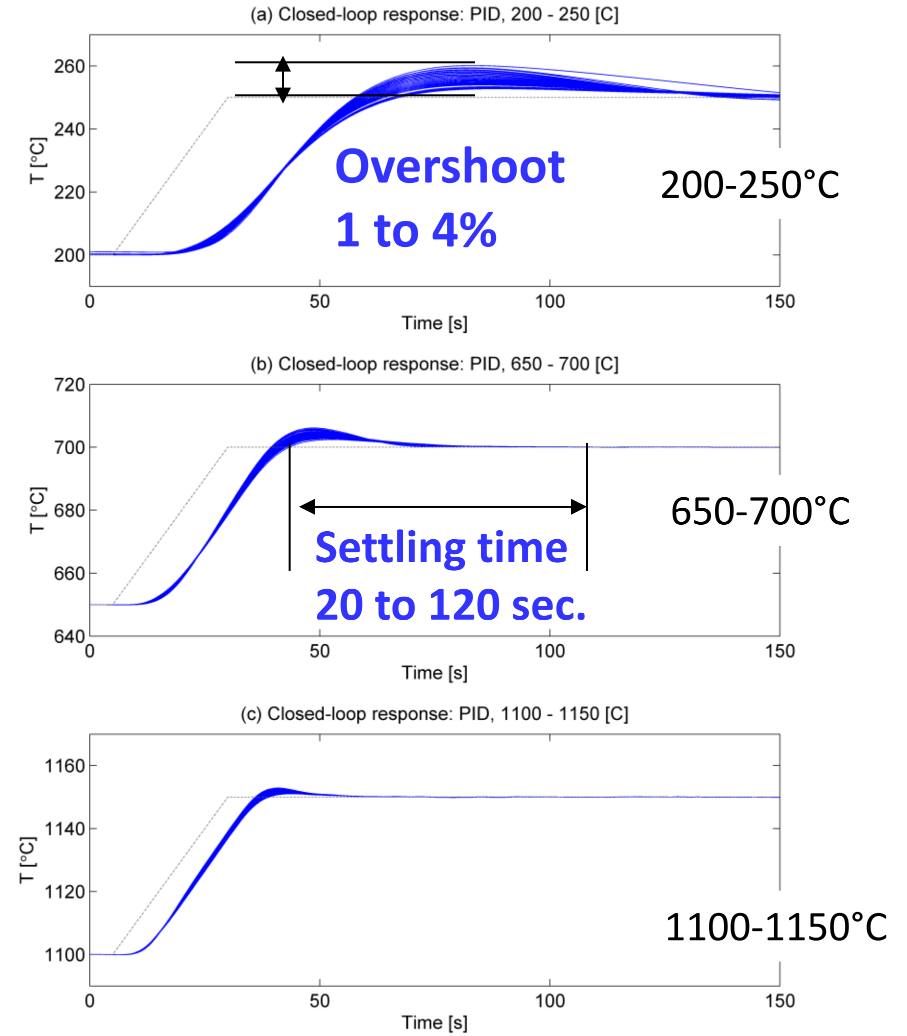
PID Control – Gain-Scheduling

- Some of the variation in system dynamics is due to temperature, and the controller will know temperature.
- Pick a different set of gains at each temperature using the AMIGO method.
- Gain selection here is biased toward good repeatability.

- By trial-and-error we chose the gain values when h=20W/m^{2}K, ε=0.2
- Simulated 2°C/s, 50°C ramp, 200 < T < 1150°C

Performance measures:

- Settling time
  - *Time from end of ramp until sensor stays within ±0.5°C*
- Overshoot
  - *How much response exceeds the reference in percent*
- Repeatability
  - *Range of settling times*
- Noise accommodation
  - *Effect of noise on control command*



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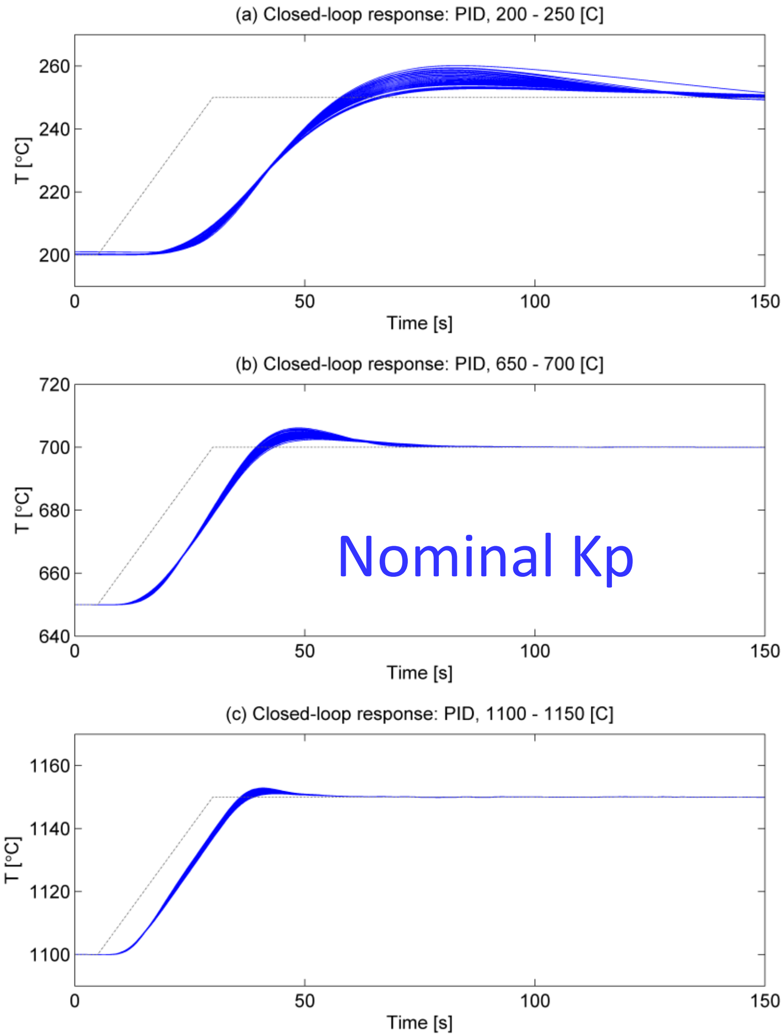
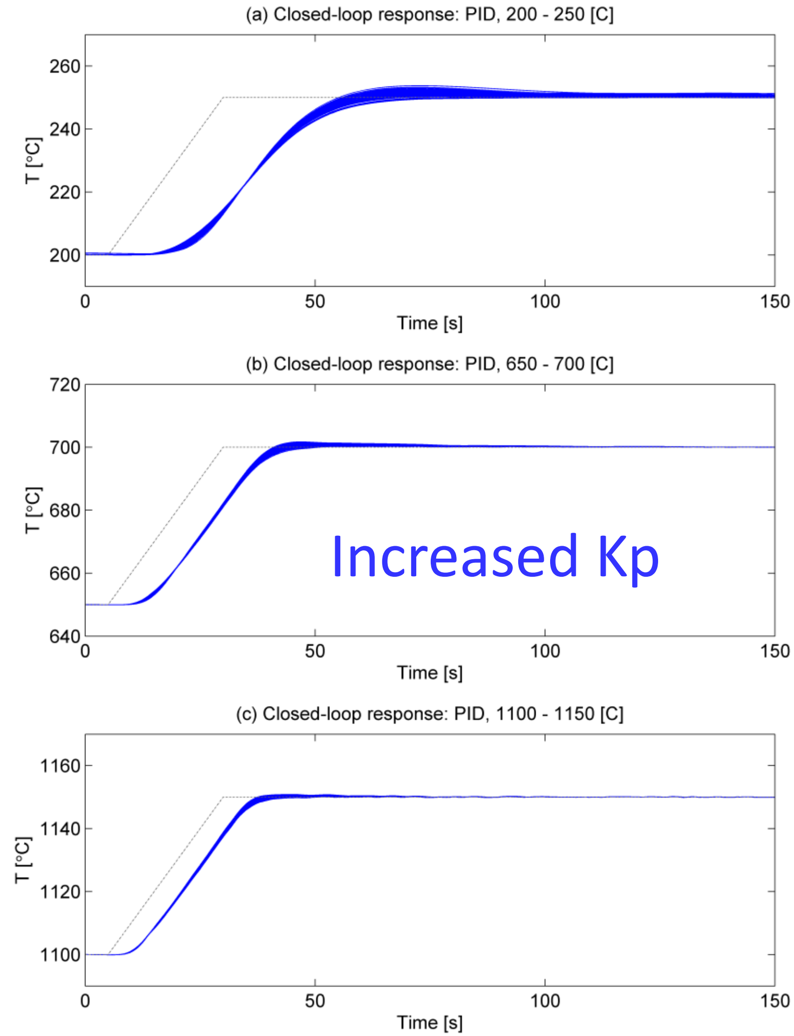
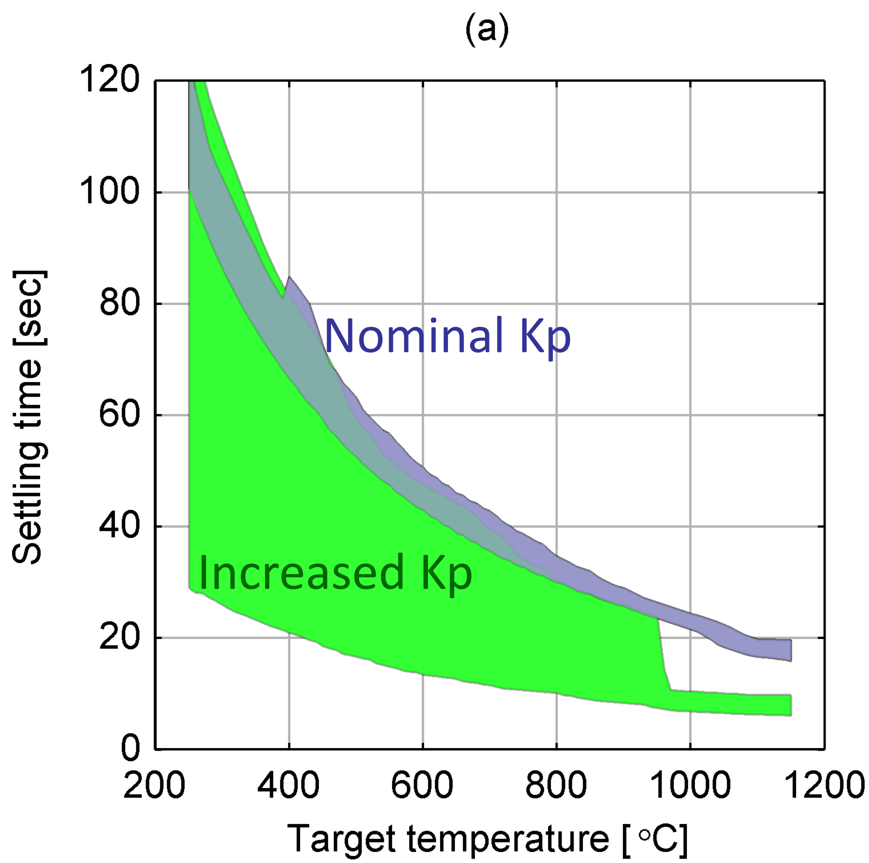
PID Control – Increased Kp

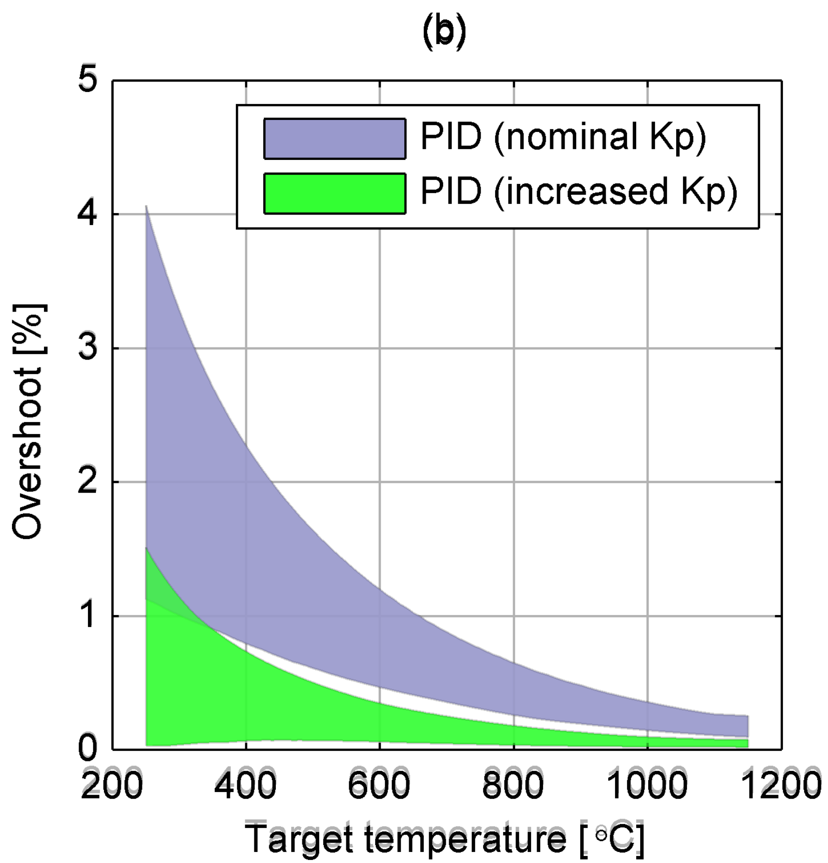




Settling time



Overshoot



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- Starting point is a linear model of the form:

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

$$y = Cx$$

- Minimize Quadratic Cost Function:

$$J_K = \frac{1}{2}\int_0^{\infty}\{x^T Qx + u^T Ru\}dt$$

- Design Feedback Controller of the Form

$$u = -Kx$$

- Tradeoffs: performance (settling time, overshoot) vs control effort, and robustness w.r.t. sensor noise and modeling uncertainties

- **Estimator Plant:**

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

$$y = Cx + v$$

- **Similar Minimization for Estimator gain L:**

$$J_L = \frac{1}{2}\int_0^{\infty}\{z^T W z + y^T V y\}dt$$

- **Final Controller Structure:**

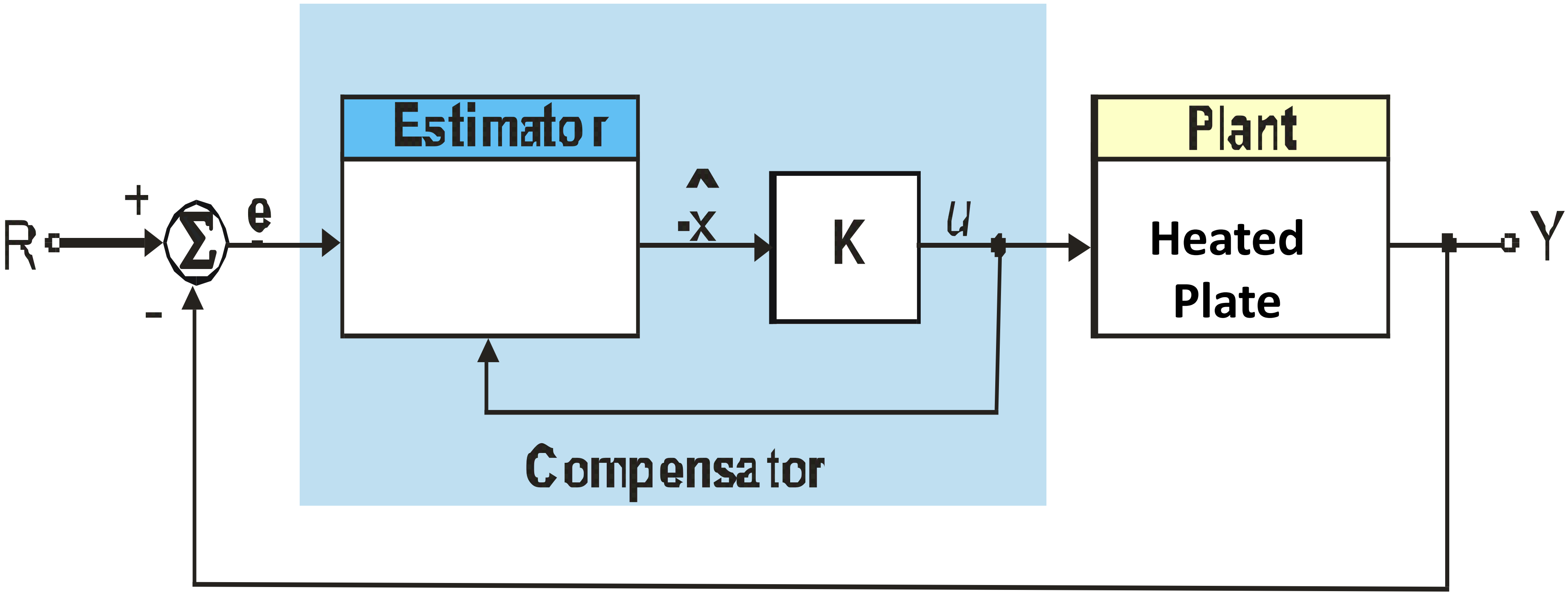
$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y})$$

$$u = -K\hat{x}$$

- **The Dynamic Feedback Controller (Compensator) is:**

$$D(s) = -K(sI - F)^{-1}L$$

LQG Control: Closed-loop System



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LQG Control – Performance

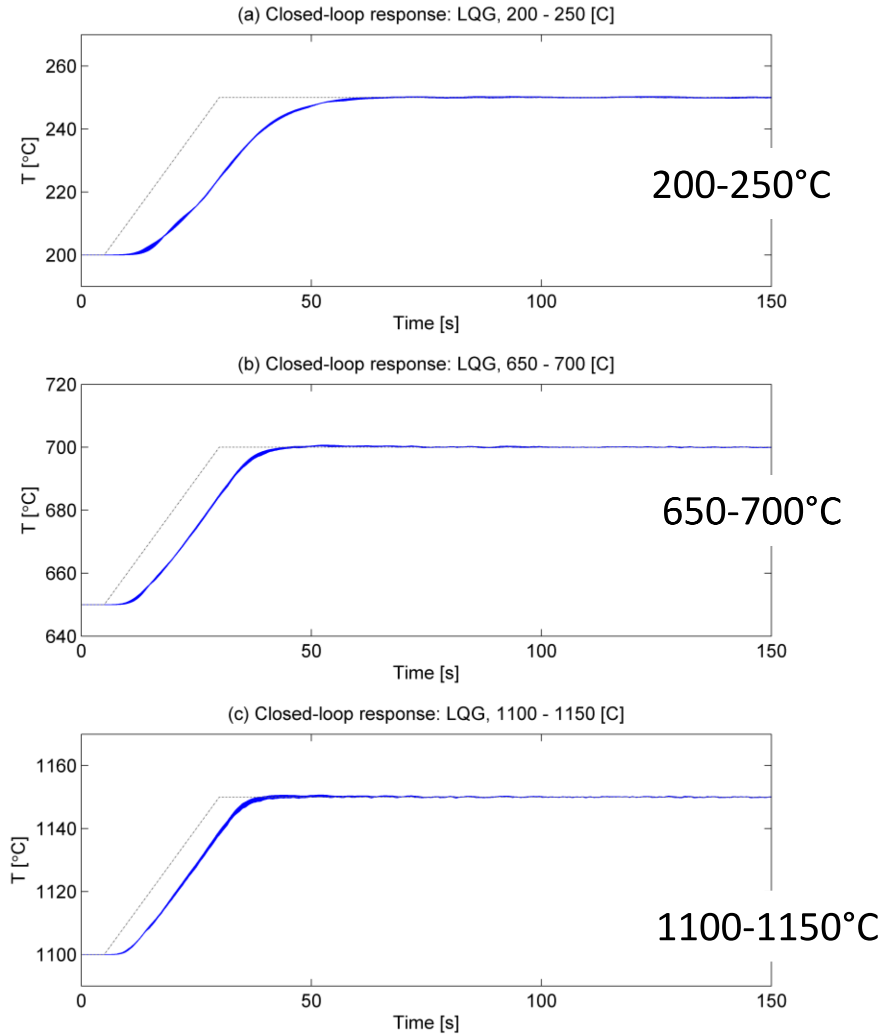
- Bryson's rule for tuning weights:

$$Q(i,i) = 1 \Big/ \text{maximum acceptable value of } \left[z_i^2 \right],$$

$$R(i,i) = 1 \Big/ \text{maximum acceptable value of } \left[u_i^2 \right].$$

Performance measures

- **Settling time**
  - *Fast settling: 10 to 25 sec.*
- **Overshoot**
  - *Very small: 0.05 to 0.15%*
- **Repeatability**
  - *Tight range in settling time & overshoot*
- **Noise accommodation**
  - *More sensitive to noise than PID*



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- Incorporate a mathematical model of the system directly into the controller.
- Often referred to as Q-parameterization or Youla parameterization.

$$C(s) = \frac{Q(s)}{1 - \hat{P}(s)Q(s)}$$

For stable P, ALL stable controllers can be expressed in this form!

Control design becomes choice of Q

$\downarrow$

We choose Q such that the closed-loop transfer function is

$$T_d(s) = \frac{\omega_d^2}{s^2 + 2\beta_d\omega_d s + \omega_d^2}$$

References for Q-parameterization Control Design

[10] D. C. Youla, J. J. Bongiorno Jr., and C. N. Lu, "Single-loop feedback-stabilization of linear multivariable dynamical plants," *Automatica*, vol. 10, no. 2, pp. 159 – 173, 1974.

[11] M. Morari and E. Zafiriou, *Robust Process Control*, 6th ed. Prentice-Hall, 1989.

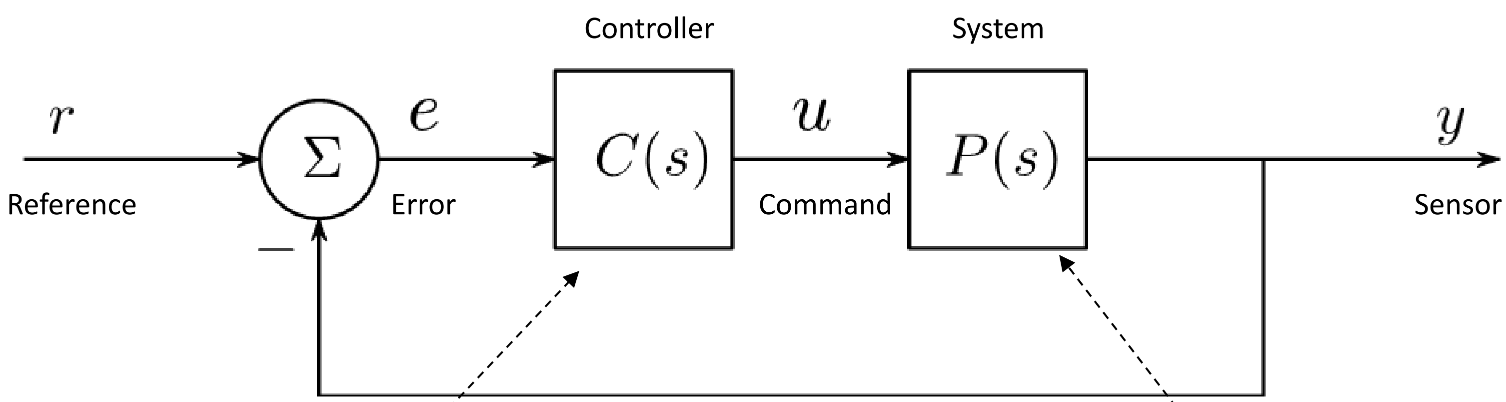
[12] S. P. Boyd and C. H. Barratt, *Linear Controller Design: Limits of Performance*. Prenctic Hall, 1991.

[13] J. C. Doyle, B. F. Francis, and A. R. Tannenbaum, *Feedback Control Theory*. Macmillan Publishing Company, 1992.

[14] P. Dorato, *Analytic Feedback System Design: An Interpolation Approach*. Macmillan Publishing Company, 1994.

Model-Based Control

- The feedback controller is assumed to have no prior knowledge of these variations in the plant.



$\hat{P}$

System Variations

$$0.2 \leq \epsilon \leq 0.8$$
$$5 \leq h \leq 100$$

The model inside the controller knows temperature (as does Gain-Scheduled PID) and the structure of the model but *does not know these parameter variations*.

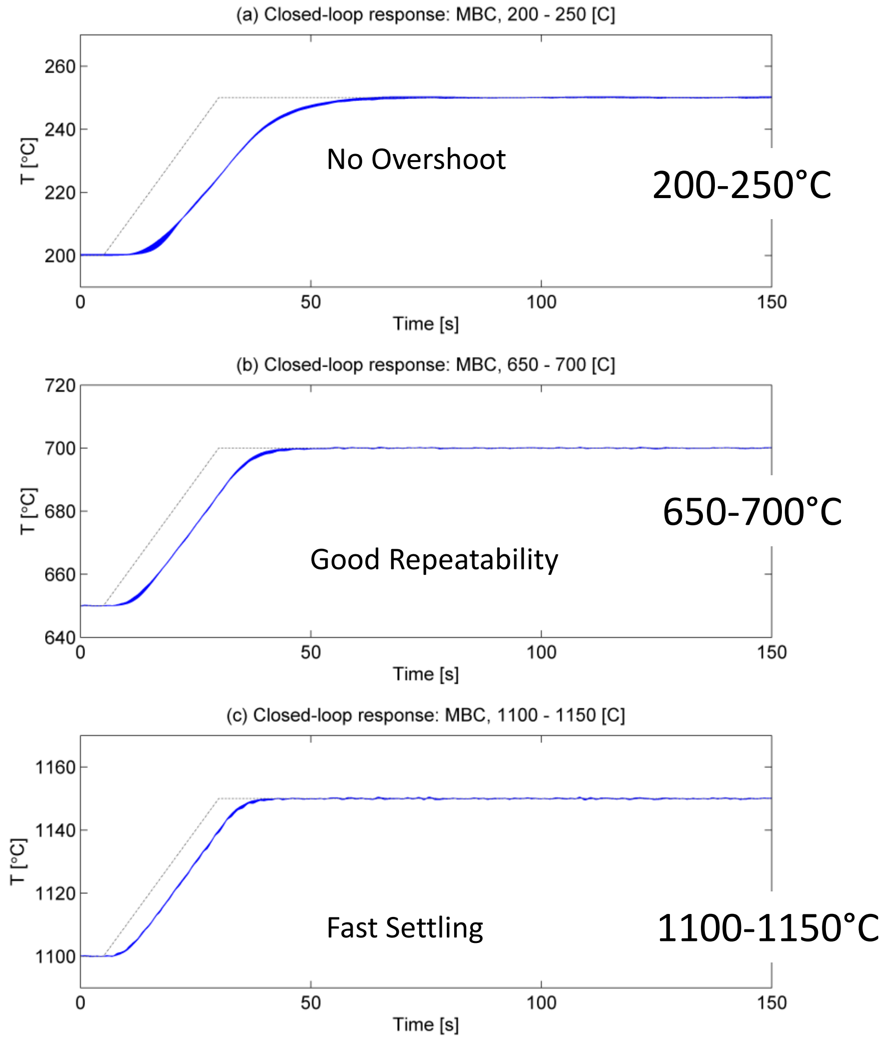
- Bandwidth of *Td* is only 'tuning knob':

$$T_d(s) = \frac{\omega_d^2}{s^2 + 2\beta_d\omega_d s + \omega_d^2}$$

The model used in the controller is not told how the model in the simulation is varying

Performance similar to LQG:

- Settling time
  - *Fast settling: 10 to 25 sec.*
- Overshoot
  - *Very small: 0.05 to 0.15%*
- Repeatability
  - *Tight range in settling time & overshoot*
- Noise accommodation
  - *More sensitive to noise than PID*



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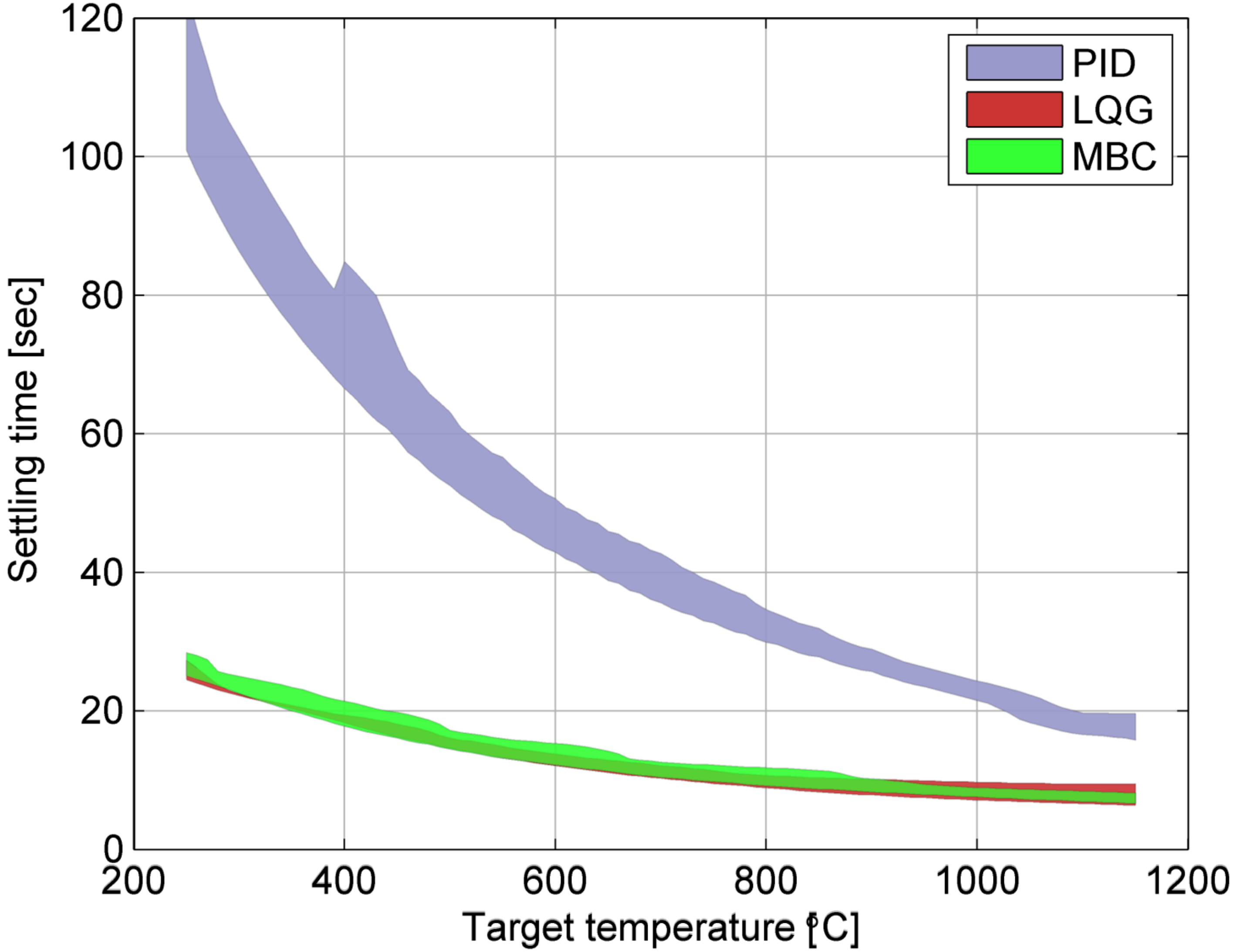
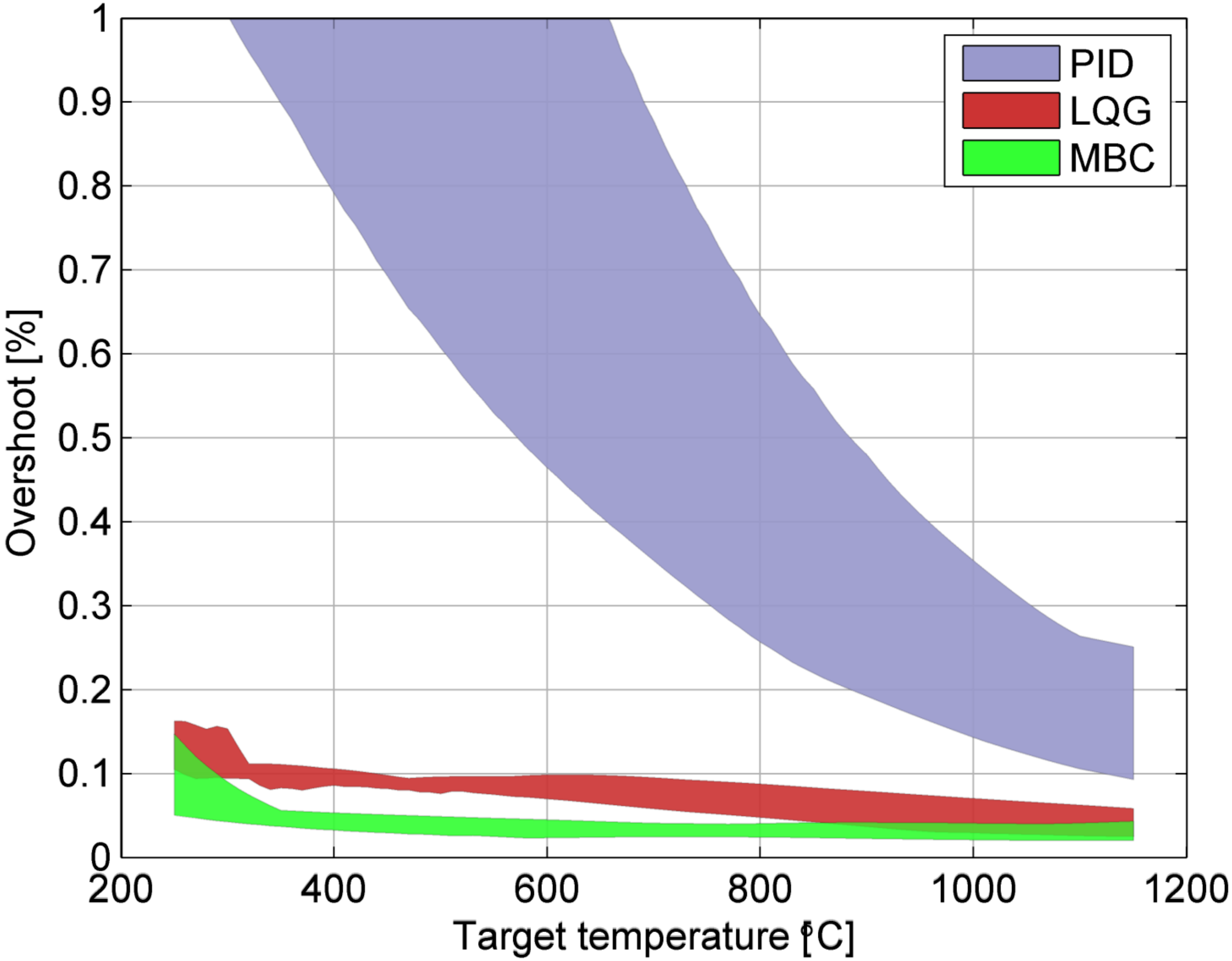
Performance Comparison: Settling Time



Performance Comparison: Overshoot



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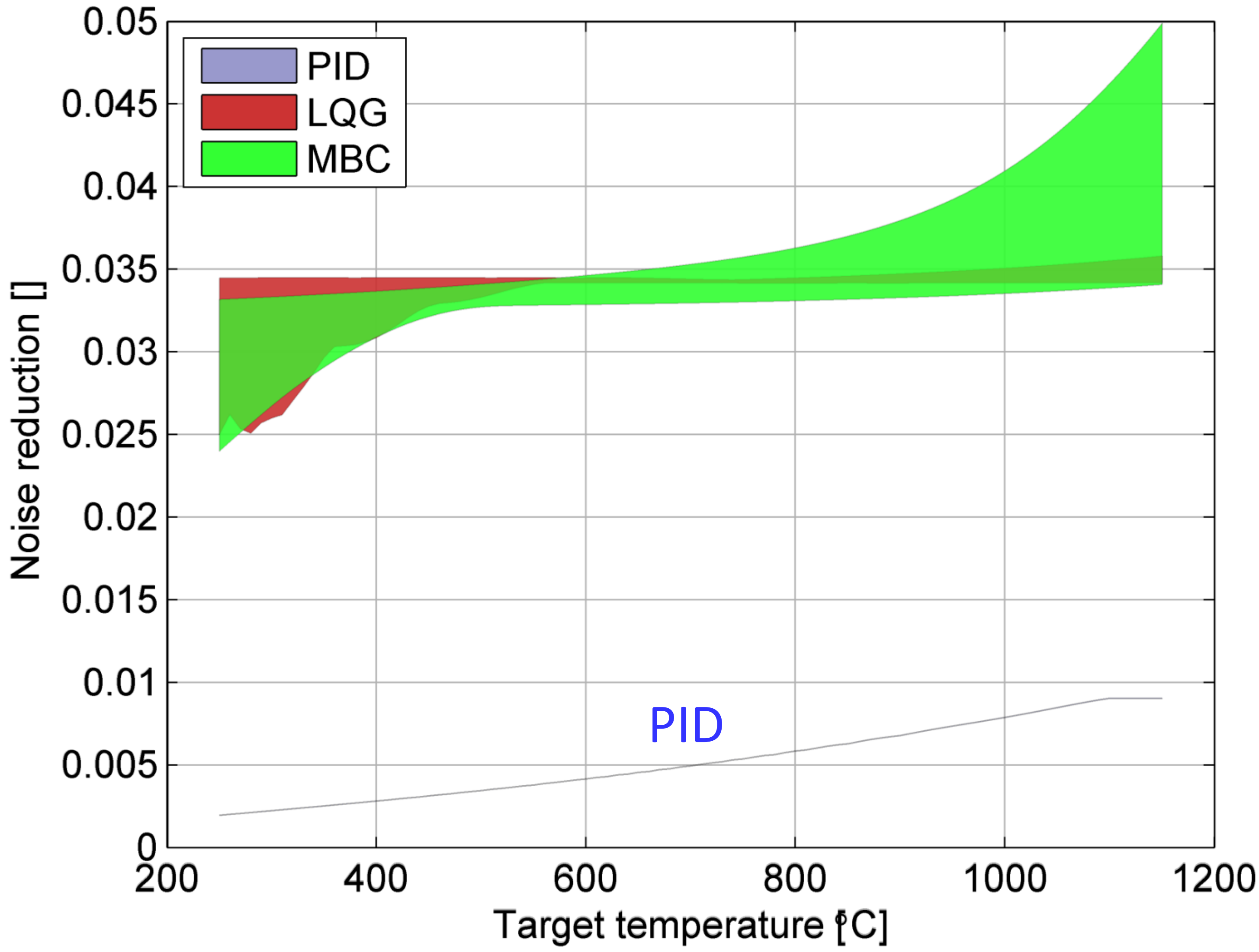
Performance Comparison: Noise Accommodation



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Summary

- **Simulations were performed to compare the robustness & performance of three different control approaches for temperature control of heated plates:**
  - ***Gain-Scheduled PID control,***
  - ***Linear-Quadratic-Gaussian (LQG) control,***
  - ***Model-Based Control (MBC).***
- **The three methods were compared with respect to:**
  - ***worst-case settling time,***
  - ***overshoot,***
  - ***robustness (repeatability),***
  - ***noise accommodation.***
- **Settling time, overshoot and repeatability (robustness) for LQG & MBC were shown to be much better than Gain-Scheduled PID, but at the expense of a slight increase in noise sensitivity.**
- **Tuning of the LQG controller is mathematically more involved, whereas the MBC tuning is more intuitive. Additionally, the MBC allows inclusion of a non-linear (physical) model.**