Example : Glasshouse Climate Control

ESE 505 & MEAM 513

Bruce D. Kothmann

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Lecture Adapted From This Paper

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MODELLING AND PIP CONTROL OF A GLASSHOUSE MICRO-CLIMATE

P.C. Young*, M.J. Lees*, A. Chotai*, W. Tych* and Z.S. Chalabi**

**Centre for Research on Environmental Systems and Statistics, Lancaster University, Lancaster LA1 4YQ, UK*

*****AFRC Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, UK***

- Suggestion for Motivated Students
  - Read the Paper
  - Write Down Stuff You Don't Understand
  - Ask Lots of Questions!
  - Read Again @ End of Semester!

Temperature Dynamics Inside Glasshouse

- "Complex, non-linear model"
- "11 coupled, non-linear, first-order differential equations"
- "Used to design and evaluate a series of controllers for the internal climate of the glasshouse"
- "Necessary to develop a reduced-order, linearized control model which adequately describes the small perturbation dynamics of the system."

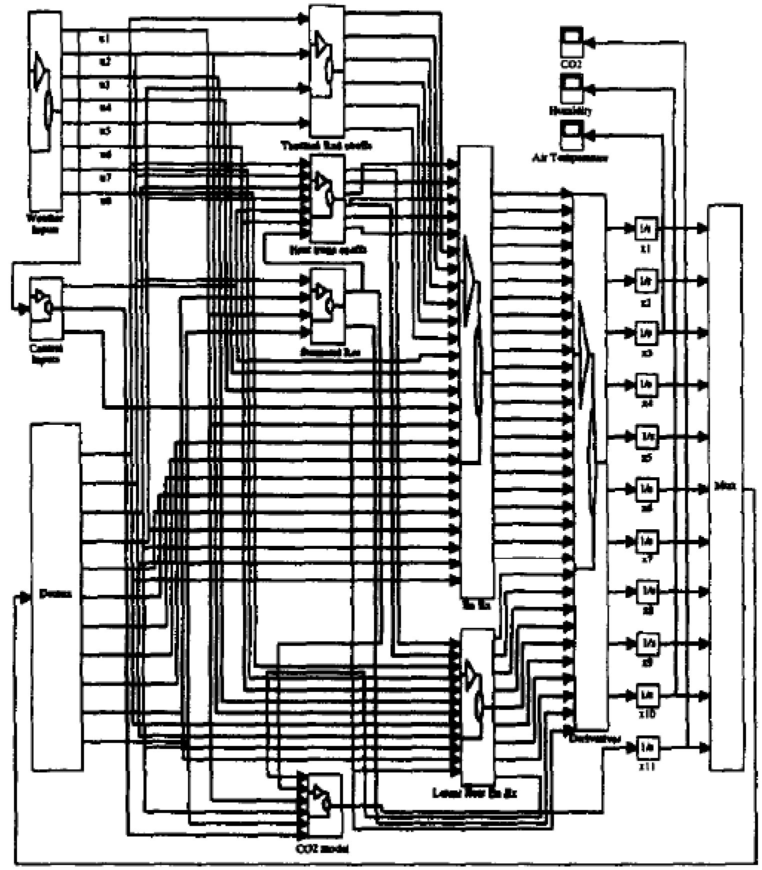
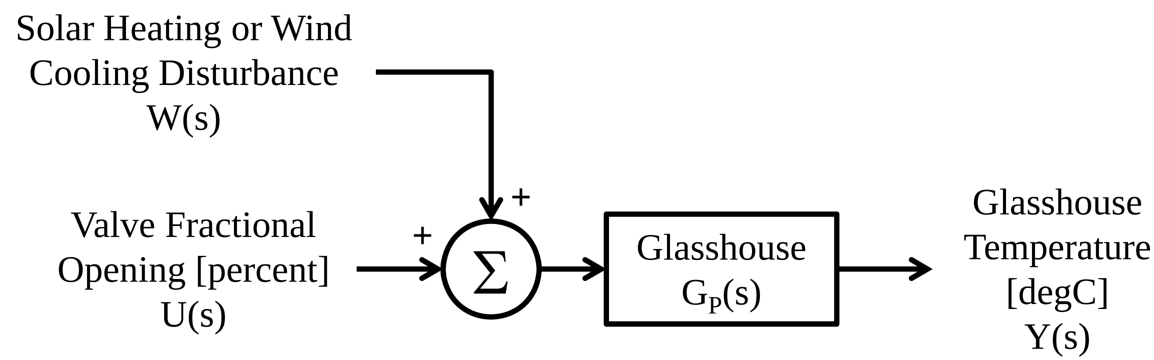


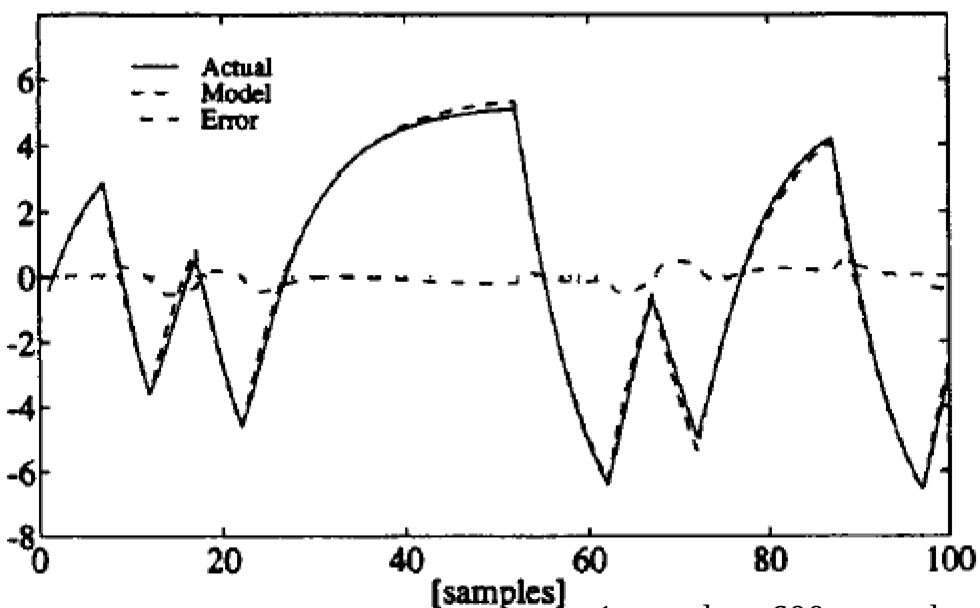
Fig 1 SIMULINK representation of the glasshouse climate model

Linear Approximation to Plant Dynamics

Complex Non-Linear Models Often Well-Approximated by Low-Order Linear Systems!



(b) First Order Model Fit and Error



1 sample = 600 seconds

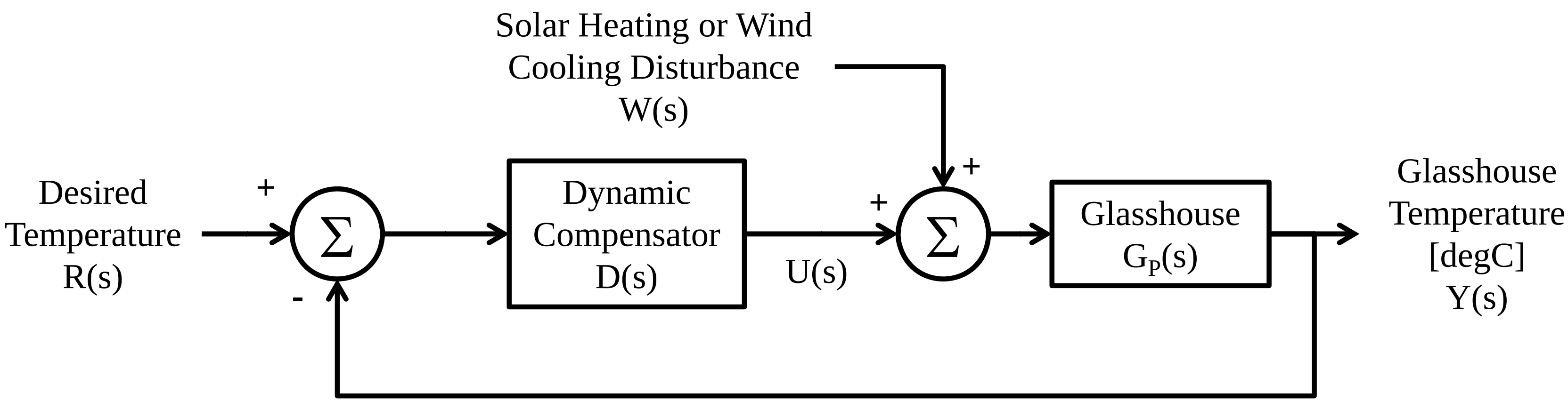
$$G_P(s) = \frac{Ae^{-T_d s}}{\tau s + 1}$$

A = 0.32 degC/percent

Td = 600 sec (10 min)

τ = 4440 sec (74 min)

A Simple Candidate Architecture



$$Y(s) = \frac{DG_P}{1+DG_P}R(s) + \frac{G_P}{1+DG_P}W(s)$$

"Loop Transfer Function" $\quad G(s) \triangleq D(s)G_P(s)$

Both Terms Have Same Denominator = $\Delta_{CL}(s)$ $\quad \Delta_{CL}(s) = 1 + G(s)$

Some Requirements

- Perfect Temperature Regulation
  - We Interpret To Mean Zero Steady-State Error
  - Need Type 1 System → D(s) Must Include Integral Feedback
- Reject Daily Temperature Swings (Solar Heating & Atmospheric Temperature)
  - Want Substantial Disturbance Rejection For 1-Per-Day Disturbances (Frequency = $2\pi/(24*3600) = 0.000072$ rad/sec)
- "Reduced Actuator Operation (to Minimize Wear)"
  - We Will Interpret As "Don't Push Crossover Frequency Higher Than Necessary to Achieve Good Disturbance Rejection"
  - Many More Advanced Ideas Here → Google "Optimal Control"
  - Minimum Fuel Usage Very Important on Spacecraft
- Rise Time ~ 1 Hour
  - I Made This Up, Based on Data in Paper ("Typical" for Tomatoes?)
- Very Little (No?) Overshoot
  - Closed-Loop Damping Ratio > 0.8

Preliminary Analysis (Ignore Delay at First)

Start with Something Very Simple: Use Only Integral Feedback

$$D(s) = \frac{K_I}{s} \quad G_P(s) = \frac{A}{\tau s + 1}$$

Look @ Closed-Loop Pole Locations

$$\Delta_{CL}(s) = 1 + \frac{AK_I}{s(\tau s + 1)} = 0$$

Multiply by s(τs+1) →

$$s(\tau s + 1) + AK_I = 0$$

"Root Locus" Varying Integral Gain

$$s(\tau s+1)+AK_I=0$$

```
Gtest = tf(A,[tau 1 0]);
rlocus(Gtest,[0:0.00001:0.001]);
```

$$\varsigma = 0.8$$

$$\Downarrow$$

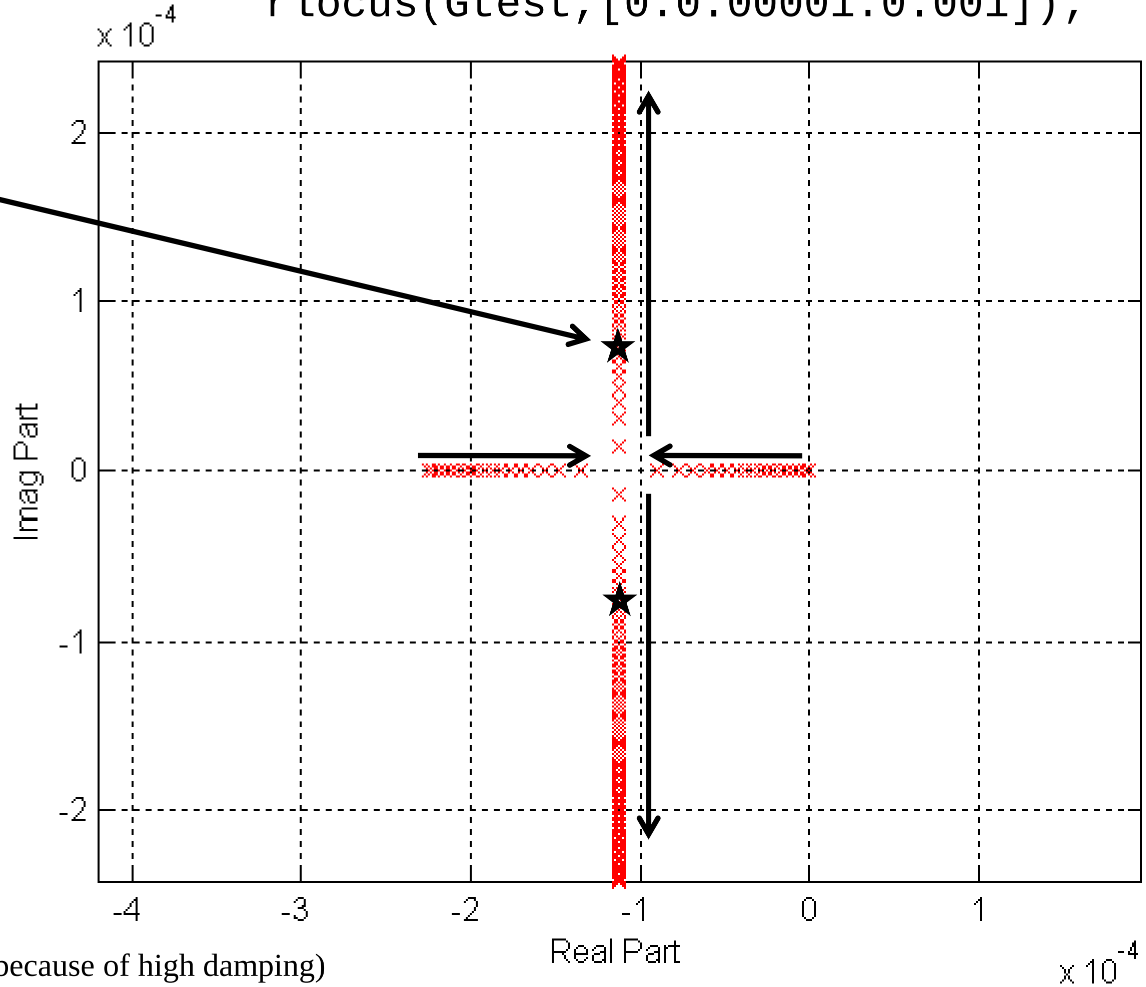
$$K_I = 0.000275$$

$$\omega_n^2 = \frac{AK_I}{\tau}$$

$$\omega_n = 0.00014 rps$$

$$t_r \approx \frac{2}{\omega_n} = 4\,hours$$

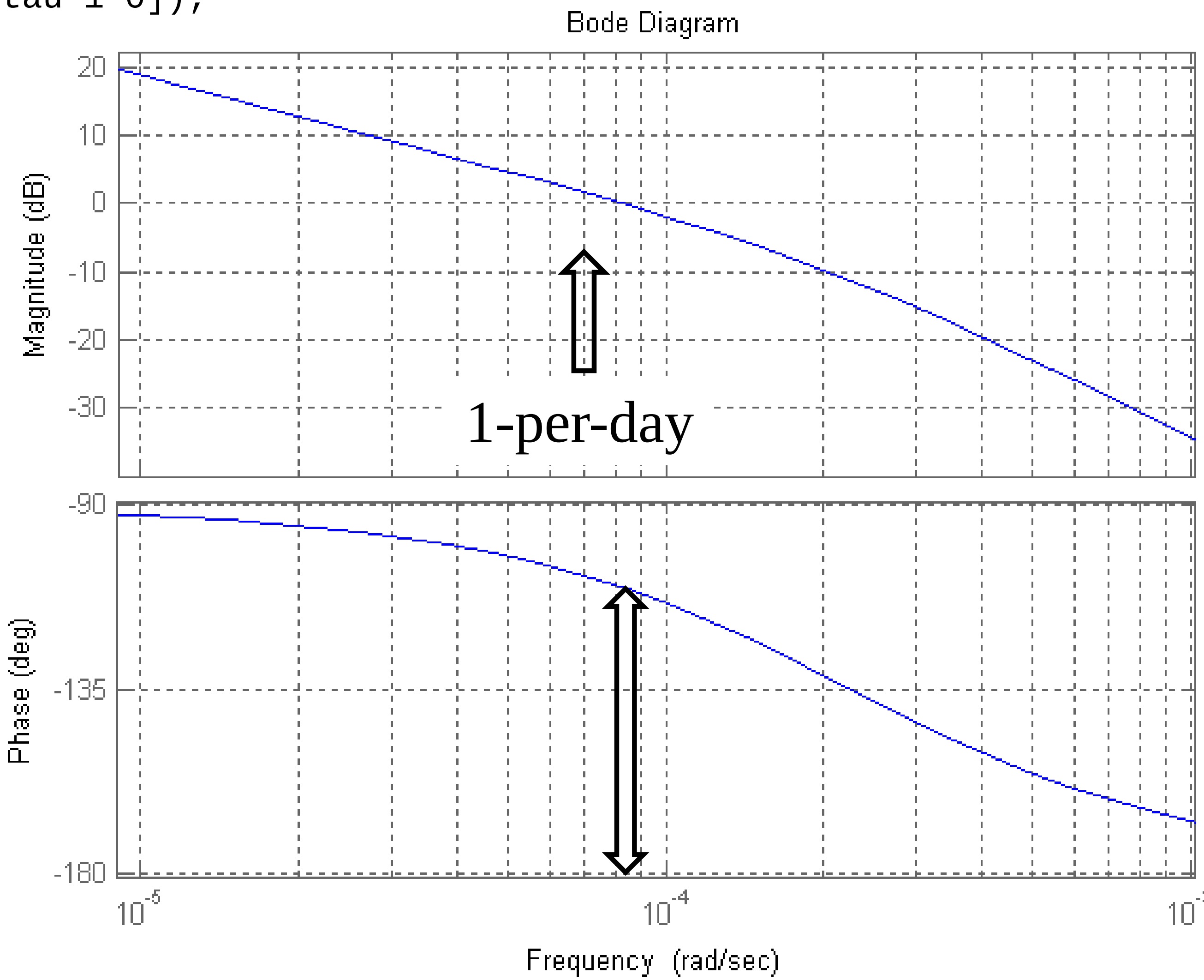
(actual rise time longer because of high damping)



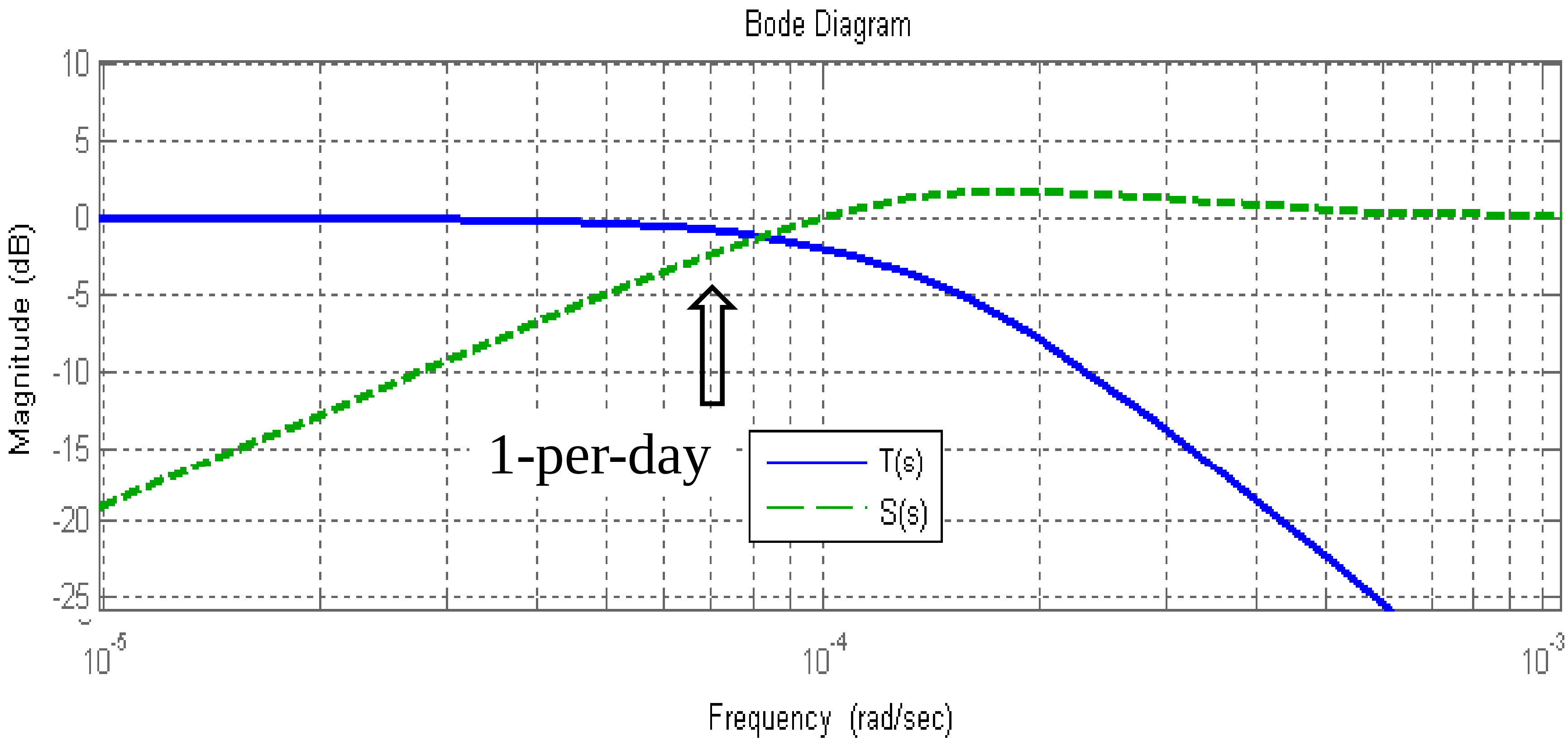
Bode Plot of Loop Gain = G(s)

```
Gtest = 0.000275*tf(A,[tau 1 0]);
bode(Gtest);
```

- Crossover Near 1/day (Too Little Rejection of Daily Temperature Effects!)
- Stability Looks Very Good (Phase @ Crossover Far From -180)



Sensitivity Bodes for Integral Feedback Only



We Need to Add Proportional Feedback

Change to PI Compensator

$$D(s) = \frac{K_I}{s} + K_P \qquad G_P(s) = \frac{A}{\tau s + 1}$$

Look @ Closed-Loop Pole Locations

$$\Delta_{CL}(s) = 1 + \frac{A\left(K_I + K_P s\right)}{s\left(\tau s + 1\right)} = 0$$

Multiply by s(τs+1) →

$$s\left(\tau s + 1\right) + A\left(K_I + K_P s\right) = 0$$

$$\Downarrow$$

$$\boxed{\tau s^2 + \left(AK_P + 1\right)s + AK_I = 0}$$

Proportional + Integral Feedback Comments

$$\tau s^2 + \left(AK_P + 1\right)s + AK_I = 0$$

- Theoretically, Can Place Closed-Loop Poles Anywhere We Want
  - KI Controls Natural Frequency
  - KP Controls Damping
- Practically, We Have Some Serious Limits
  - Thermal Control System Has Limited Heating Capability (Can't Add Energy Quickly Enough to Increase Temperature Arbitrarily Fast)
  - Remember Our "Reduced Actuator Operation" Requirement!
  - We Ignored Effects of Delay (Remember—Always Destabilizing!)
- Actual Design Chosen for Good Rejection of 1-per-day Disturbances, Quick Response & Low Actuation Use
  - KP = 9.9
  - KI = 0.0046 (~17X Larger Than with KI Alone!)

Effect of Proportional-Only Feedback with Delay

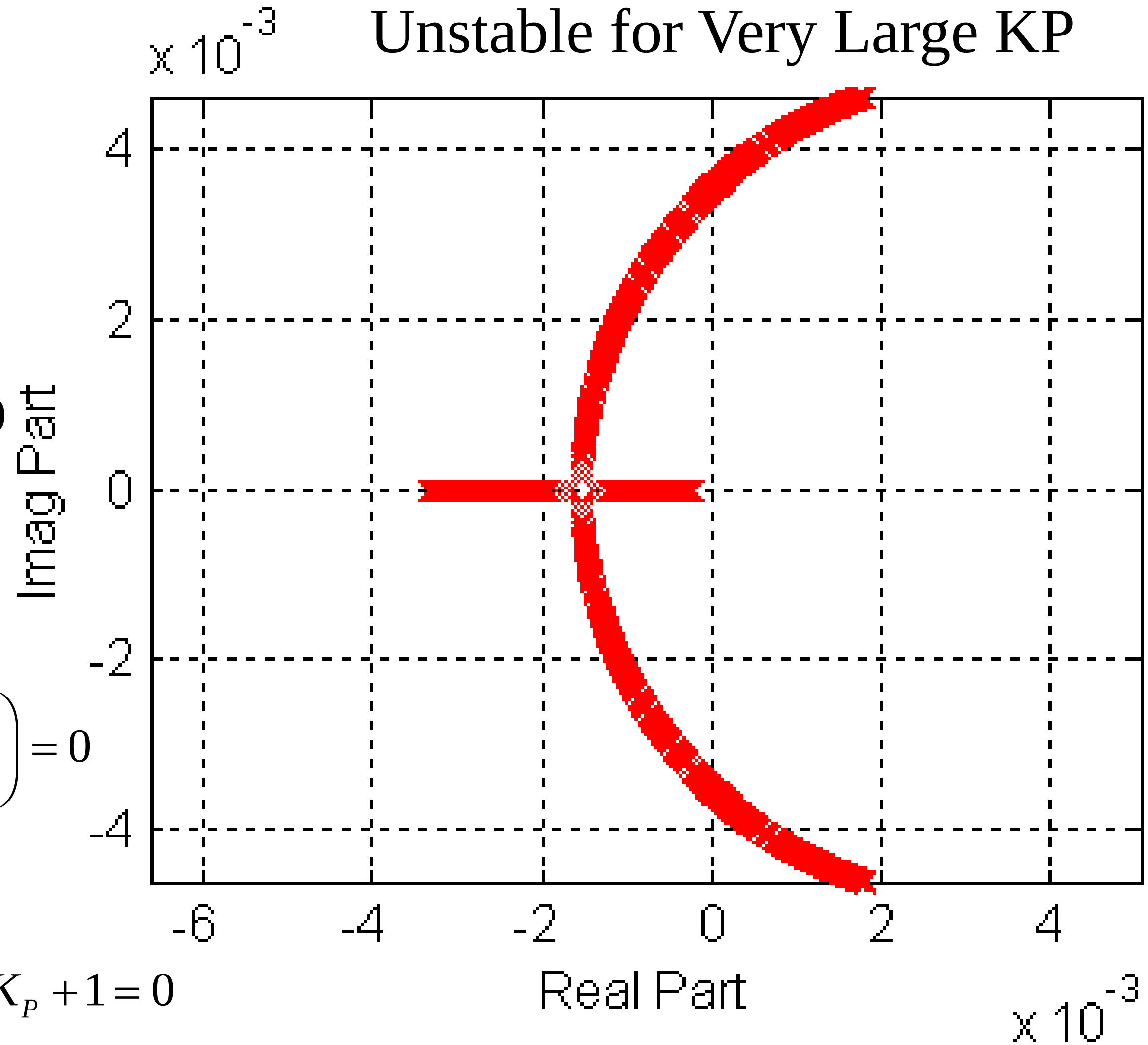
$$G_P(s) \approx \frac{A\left(-\frac{T_d}{2}s+1\right)}{(\tau s+1)\left(\frac{T_d}{2}s+1\right)}$$

$$\Delta_{CL}(s) = 1 + \frac{AK_P\left(-\frac{T_d}{2}s+1\right)}{(\tau s+1)\left(\frac{T_d}{2}s+1\right)} = 0$$

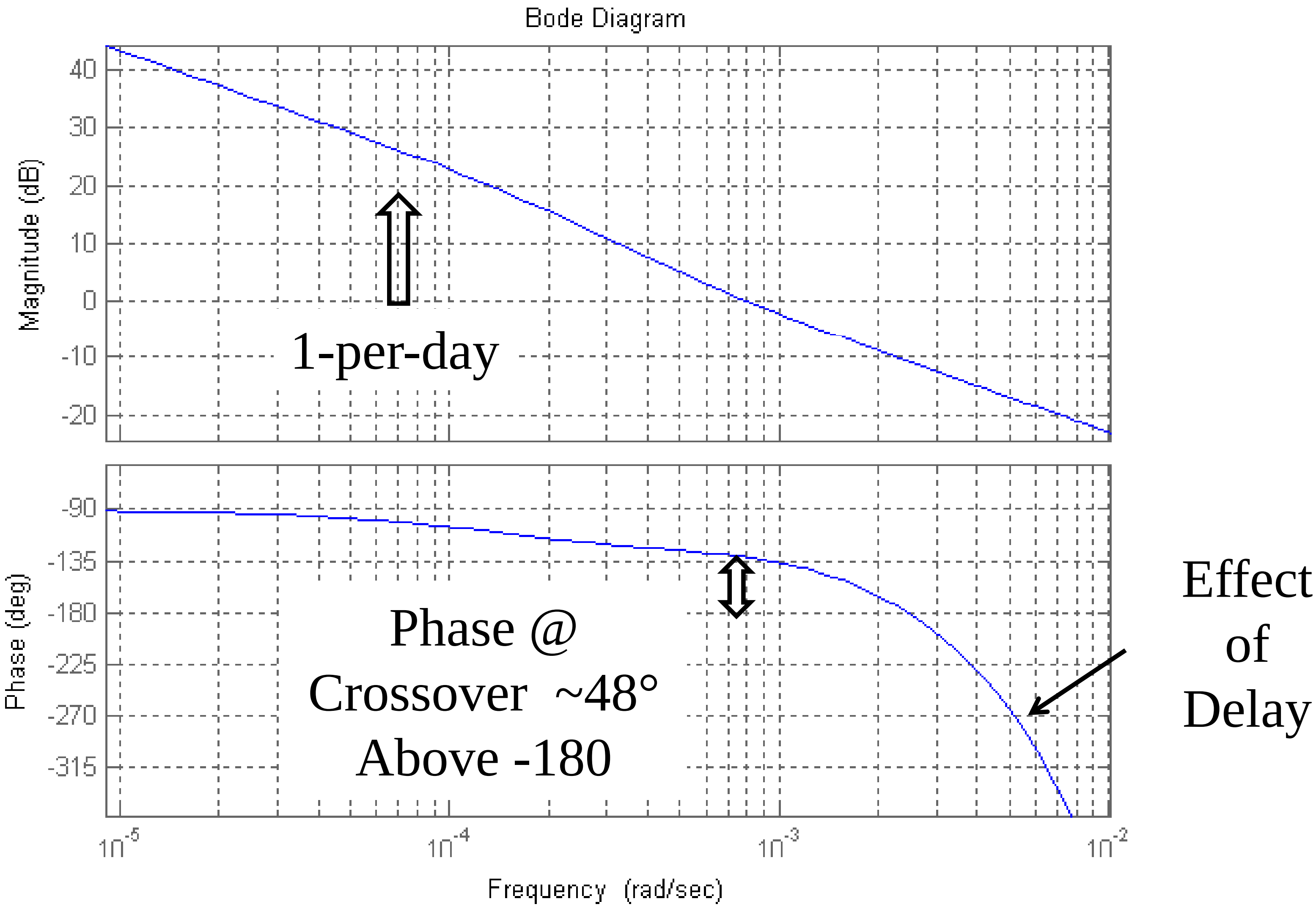
$$(\tau s+1)\left(\frac{T_d}{2}s+1\right) + AK_P\left(-\frac{T_d}{2}s+1\right) = 0$$

$$\frac{\tau T_d}{2}s^2 + \left(\tau + \frac{T_d}{2} - AK_P\frac{T_d}{2}\right)s + AK_P + 1 = 0$$

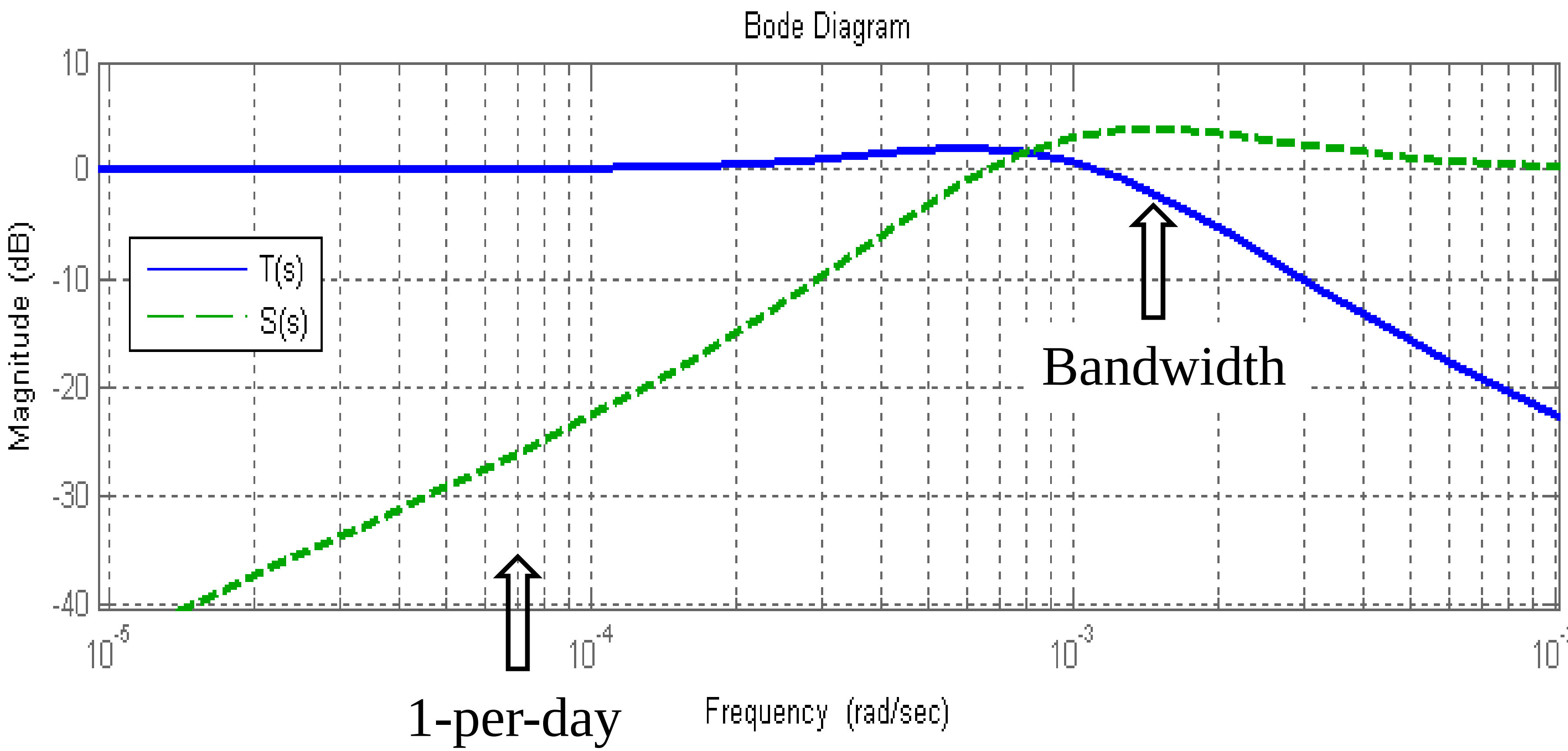
Unstable for Very Large KP



Bode Plot of Final Loop Transfer Function G(s)

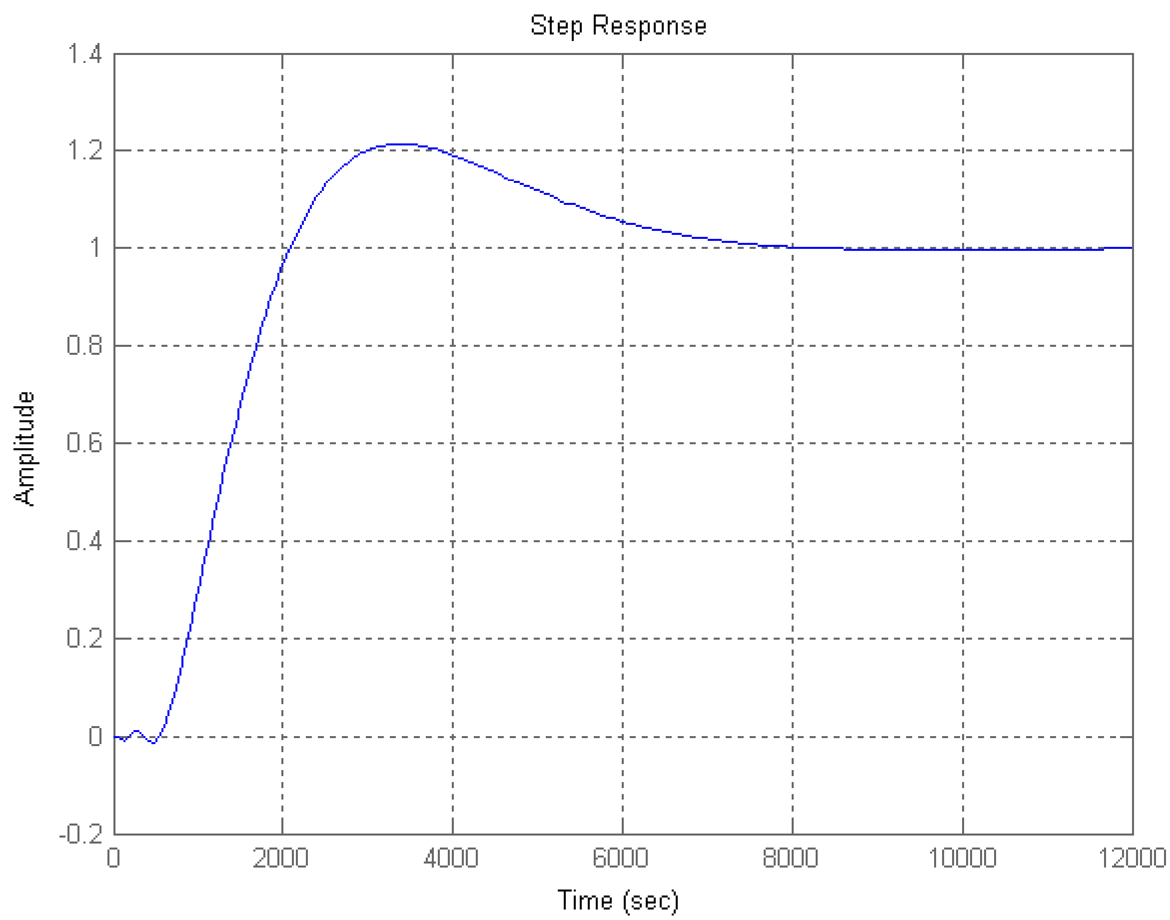


Sensitivity Bodes for Final Controller

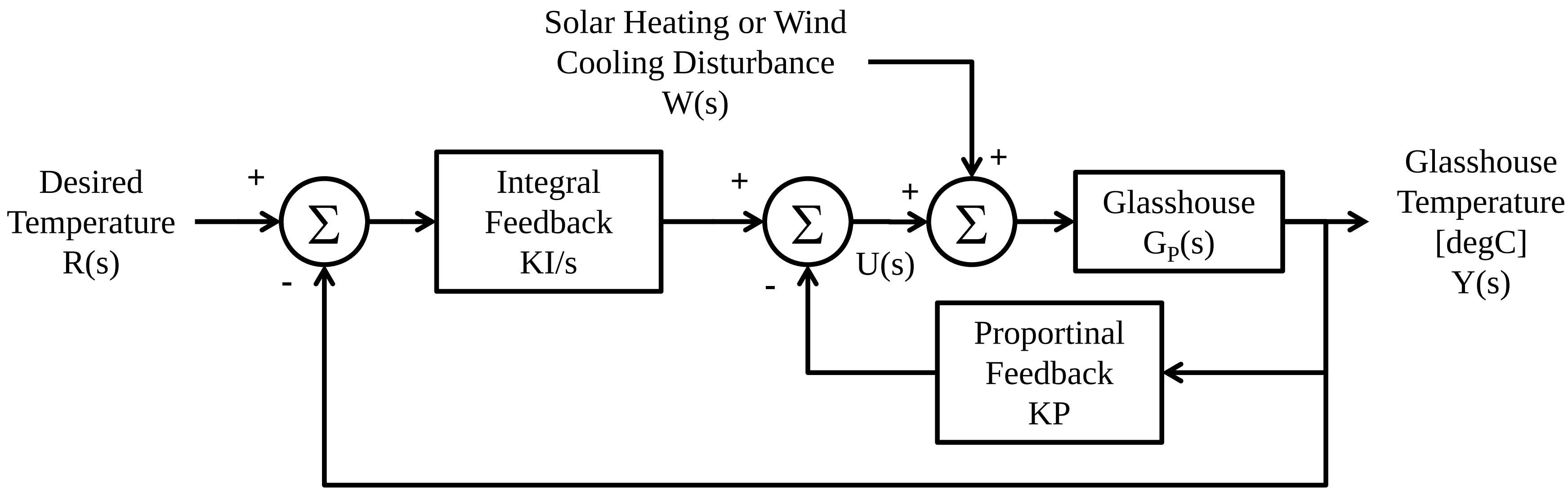


Step Response for Final Controller

- Oops! Zero in Closed-Loop Generates More Overshoot Than Desired, Despite Very High Damping Ratio!
- Fast Response Suggests Possible Over-Use of Actuator!

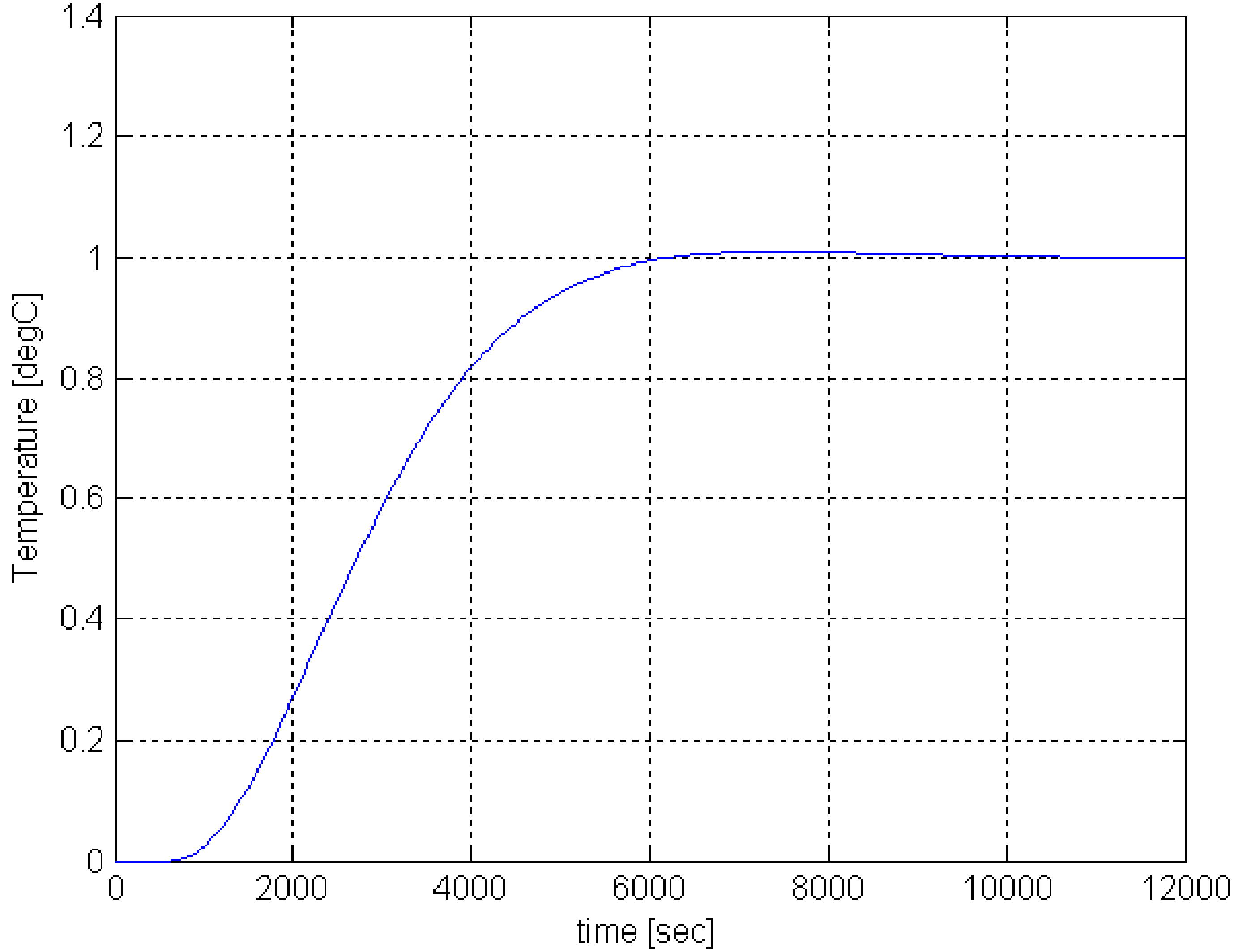


Simple Solution : Put KP on Feedback Only

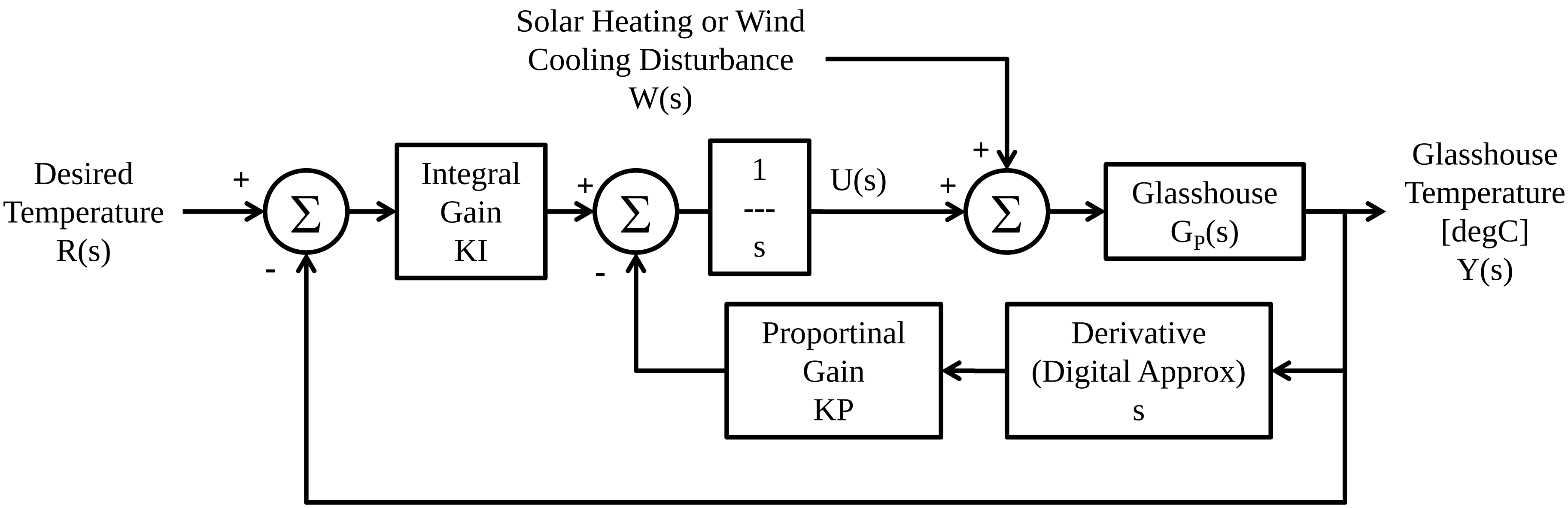


- Closed-Loop Denominator Unchanged
- Disturbance Rejection Unchanged
- Numerator of Y(s)/R(s) Has No Zero with This Architecture
  – Lower Actuator Usage
  – Overshoot Eliminated (Slightly Longer Rise Time)

Step Response with Modified Final Design



More Details of Actual Implementation…



- Proportional Feedback Implemented as Integrated Derivative!
- Integrator Output Limited
  - Prevents "Integrator Windup" With Persistent Steady Errors When Heating System Unable to Keep Up with Extreme Conditions
  - MANY Other Anti-Windup & Other Limiting Schemes Exist

Actual Implementation Using Digital Computer

$$\frac{du}{dt} = K_I\left(y - r\right) + K_p\frac{dy}{dt}$$

$$\frac{u(t) - u(t - T_s)}{T_s} \approx K_I\left(y(t) - r(t)\right) + K_p\frac{y(t) - y(t - T_s)}{T_s}$$

$$u(t) = u(t - T_s) + T_s K_I\left(y(t) - r(t)\right) + K_p\left(y(t) - y(t - T_s)\right)$$

New Control = Old Control + Linear Combination of New Measurement, Old Measurement, New Command

We Need to Learn How to Do This Carefully!