TMG Simulation of a Digital Proportional-Integral-Differential (PID) Heater Controller

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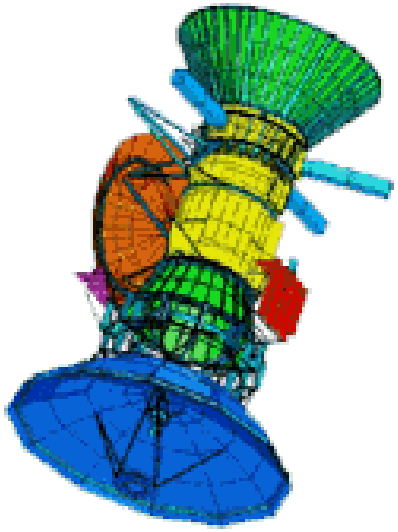
Introduction

- This presentation will demonstrate the use of I-DEAS TMG to simulate both an analog and a digital PID controller acting on a simple thermal system.
- Emphasis will be placed on the difference between analog and digital control and the characteristics unique to the digital implementation of PID control.

What is PID Control?

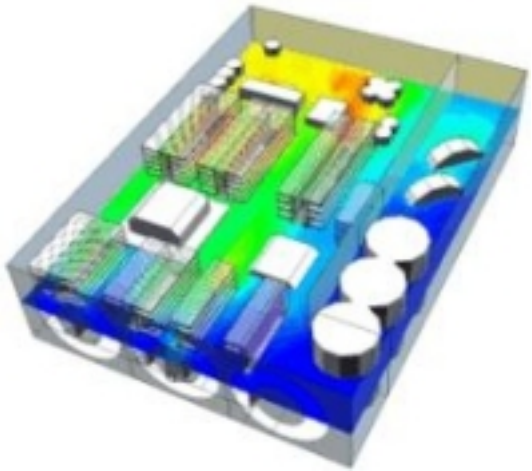
- PID control is a method of process control used extensively in industry to optimize performance of mechanical, electronic, thermal, and pneumatic systems.
- Although this presentation deals only with PID control, a variety of other control schemes, such as lead and/or lag compensation, can be simulated with this same approach.

Thermal PID Example Applications



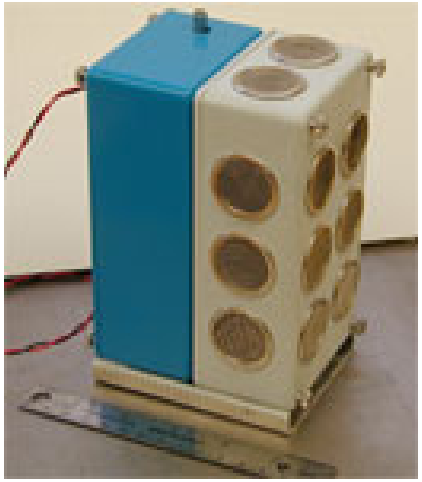
- Spacecraft components require thermal control – reflectors and optics often have strict temperature requirements that must be maintained across a spectrum of harsh orbital thermal environments.

Thermal PID Example Applications



- Electronics are sensitive to temperature. Thermal control is needed to maintain acceptable temperatures and to avoid overheating.

Thermal PID Example Applications



- Fuel cell performance is strongly dependent on maintaining proper temperature on the working surfaces of a cell. A thermal control system can help minimize both the time needed to reach optimum working temperature, and the temperature fluctuation of a cell's critical surfaces once the set temperature is reached.

PID Control in TMG

- Recent versions of TMG do provide PID simulation through a specially defined thermostat entity; however, this paper presents an implementation of PID control through the use of a user-defined subroutine.
- User-defined subroutines provide the flexibility needed to implement digital control.

Analog vs. Digital

- Analog systems are continuous.
- Digital systems are discrete.
- Example: a 100 watt heater.
  - A 100 W analog heater can supply any amount of power between 0 W and 100 W.
  - A 4-bit 100 W digital heater can supply any one of $2^4 = 16$ discrete amounts of power between 0 W and 100 W.

Example 4-bit Digital Heater

- If the digital heater powers are linearly spaced, then the available power levels are:

bits	power (W)	bits	power (W)
0000	0.00	1000	53.33
0001	6.67	1001	60.00
0010	13.33	1010	66.67
0011	20.00	1011	73.33
0100	26.67	1100	80.00
0101	33.33	1101	86.67
0110	40.00	1110	93.33
0111	46.67	1111	100.00

When are Digital Effects Important?

- Digital effects are important when the differences between digital and analog values are significant.
- If there are many digital “steps” in the range of interest then the difference between analog and digital is small.
- If there are few digital “steps” in the range of interest then the difference between analog and digital is significant.

Thermal Model

- The thermal model consists of two annular heater regions behind a circular plate.
- The plate is to be controlled to a temperature of 10°C.
- Each of the two annular heater regions is divided into three independent heaters.
- There are six temperature sensors on the control plate – one above each heater.

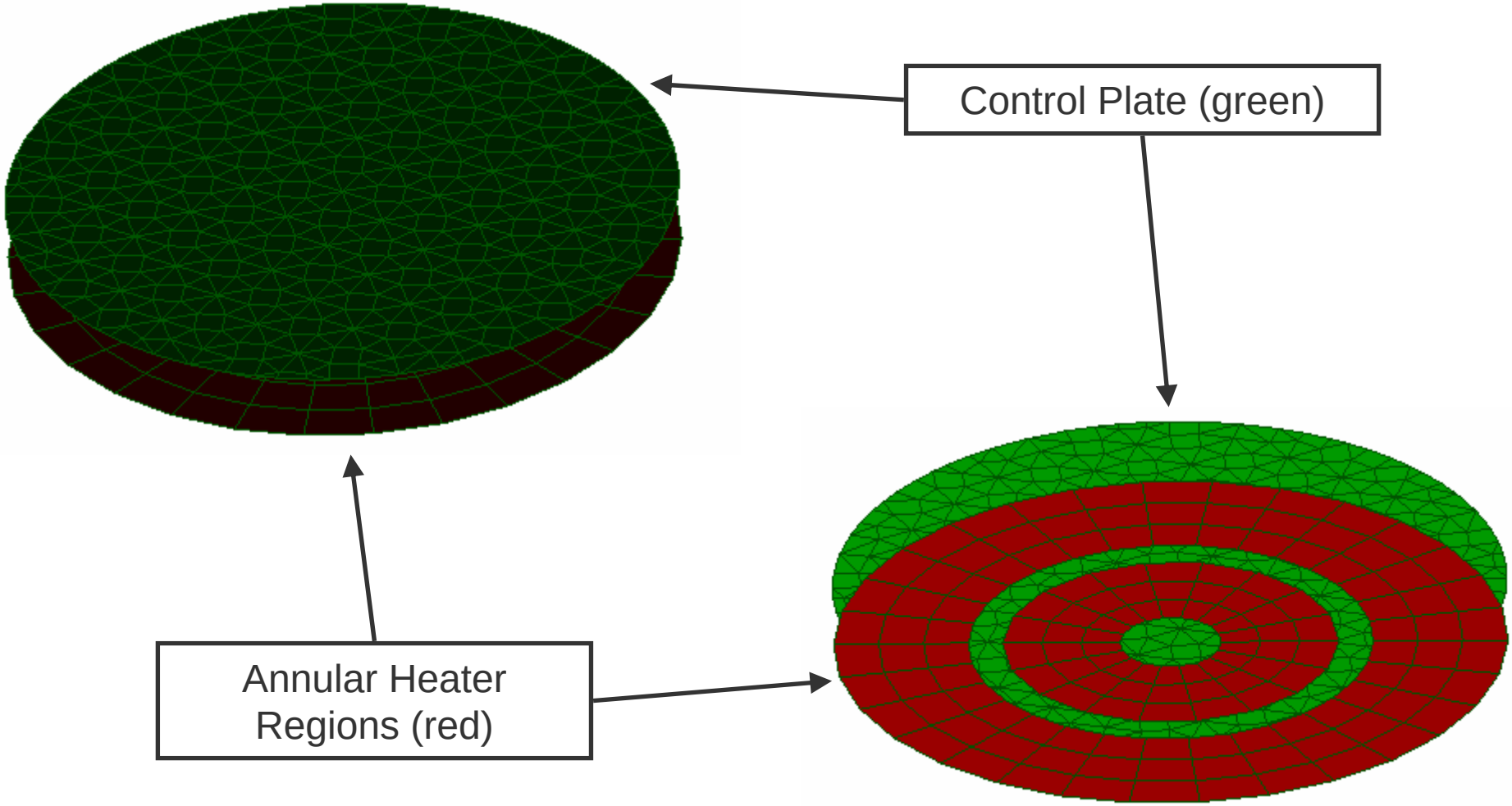
Thermal Model (continued)

- In order to produce a spatially and temporally varying disturbance heat load on the system it was partially surrounded by randomly generated shadowing surfaces and placed in a complex orbital environment. This environment was created to test the performance of the control system and its ability to maintain the desired temperature on the control plate.

Thermal Model Digitization

- The digital temperature sensors are modeled as having perfect accuracy, but 0.1°C precision.
- Temperature values returned by the sensor are: …9.70, 9.80, 9.90, 10.00, 10.10, 10.20,…
- The digital heater is 8-bit.
- There are 256 heater powers available between 0 watts and maximum power.
- Heater powers are linearly spaced.

Finite Element Model

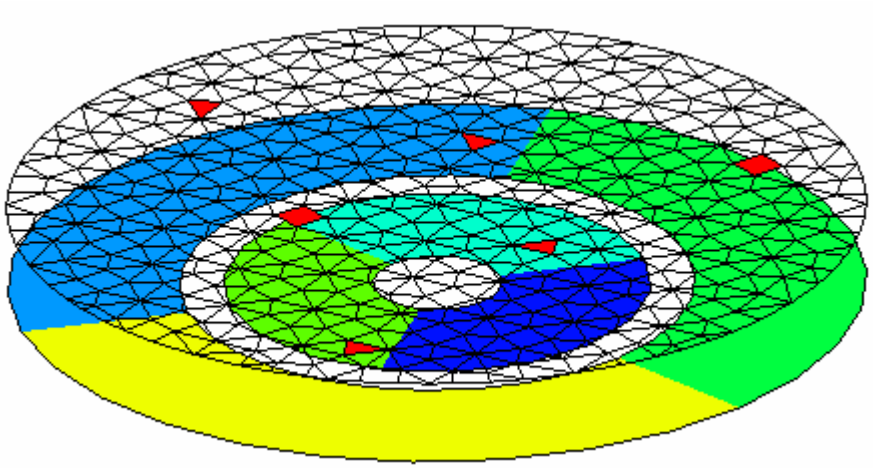


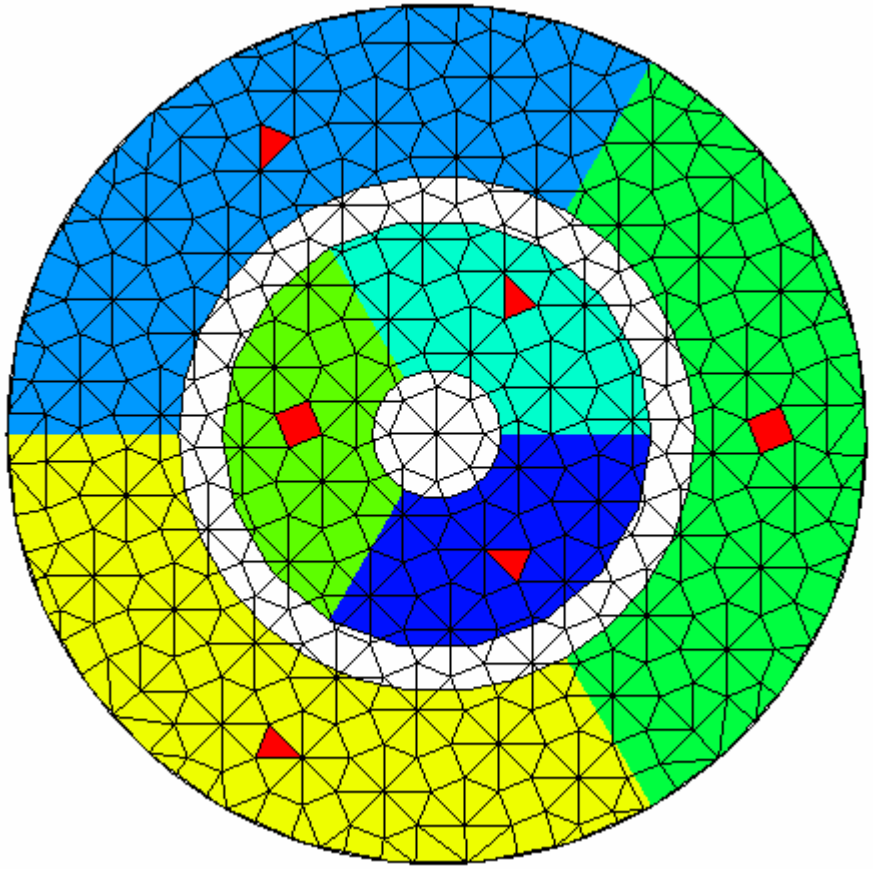
Heater Regions and Temperature Sensor Locations

Heater Regions: blue, green, and yellow

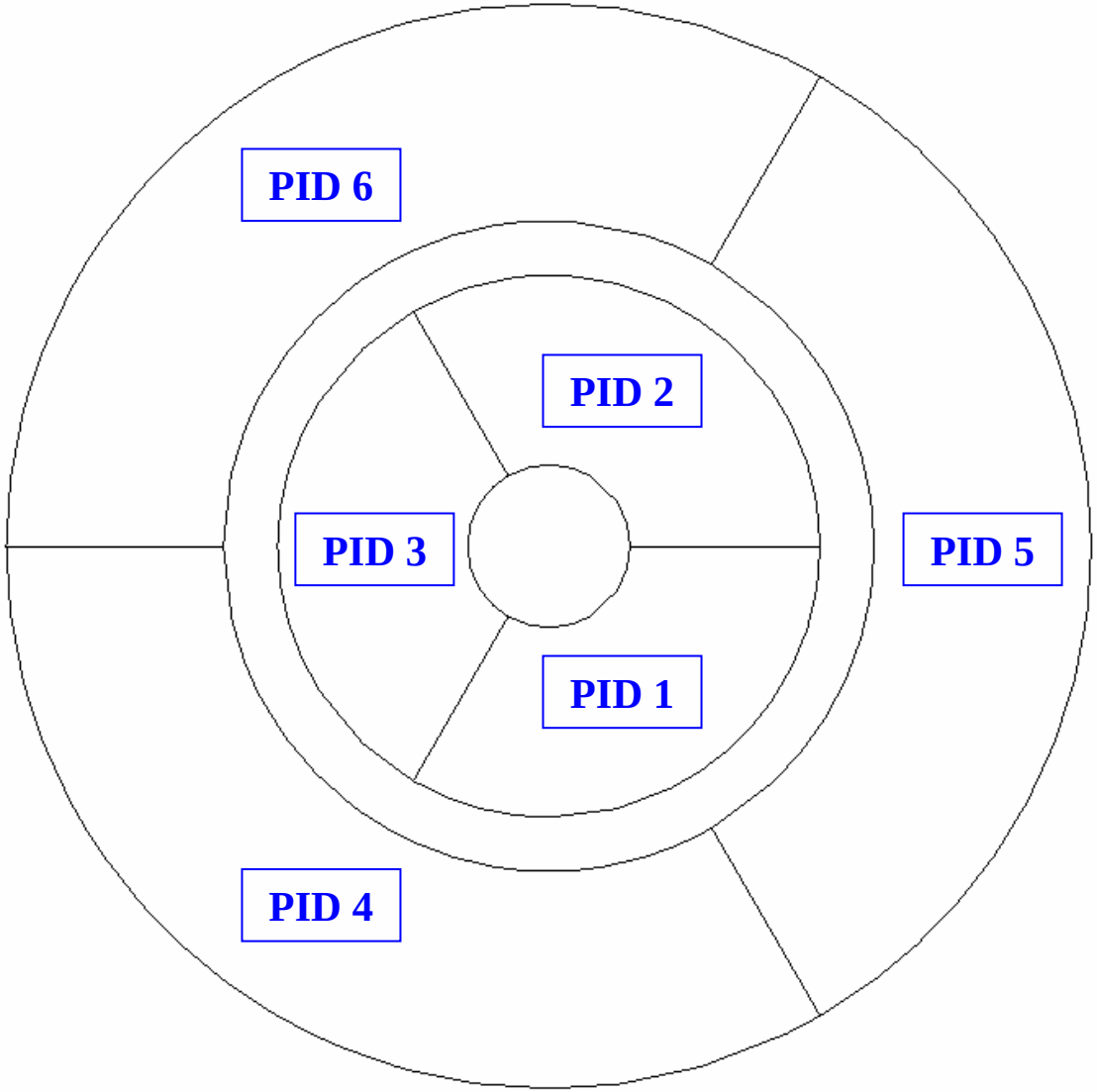
Temperature Sensor Locations: red

Control Plate Outline and Mesh: black

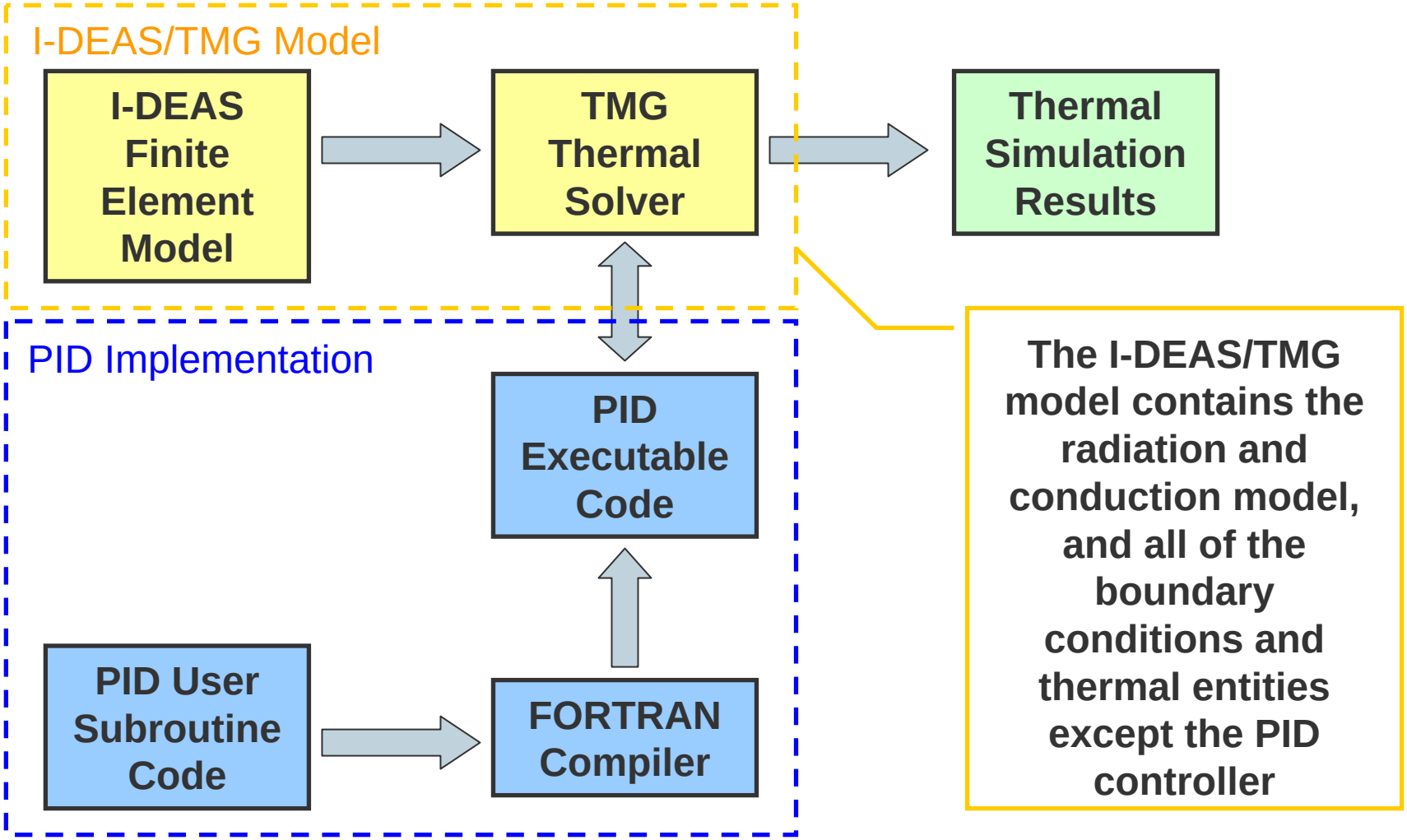




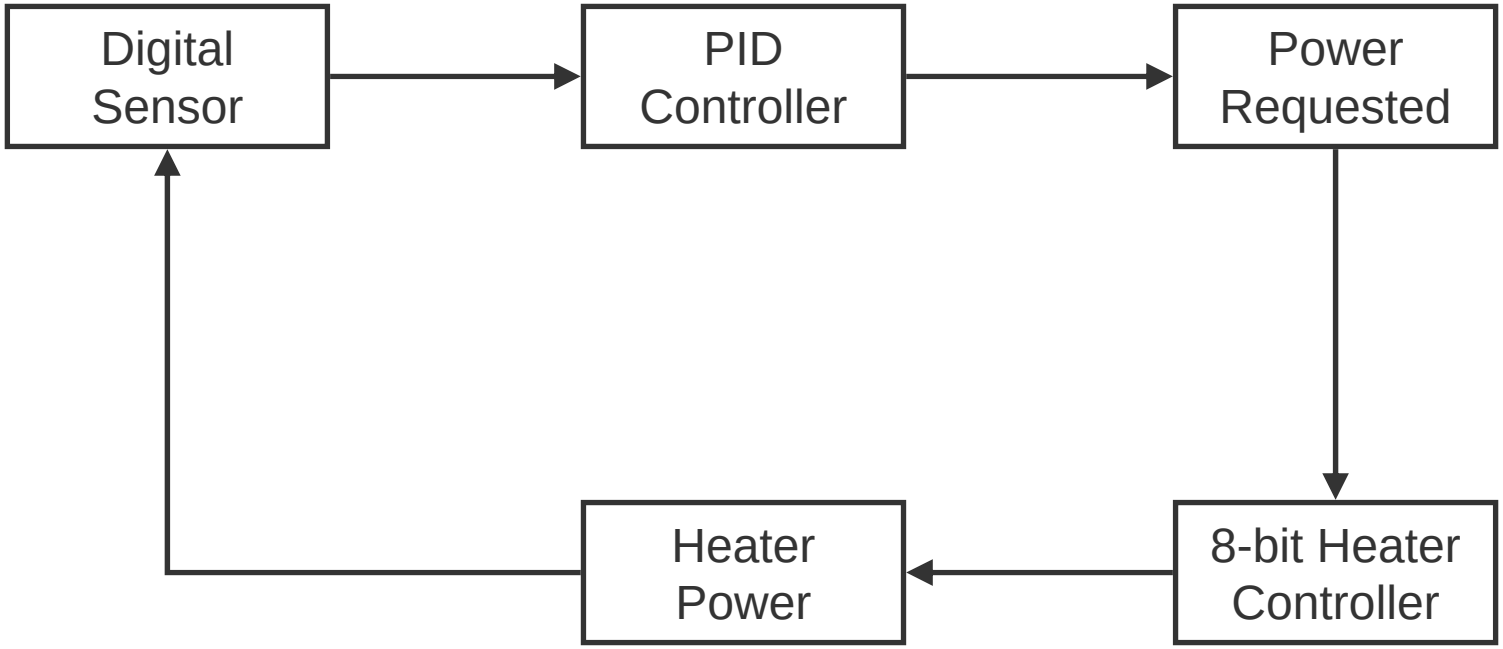
PID Heater and Sensor Numbering



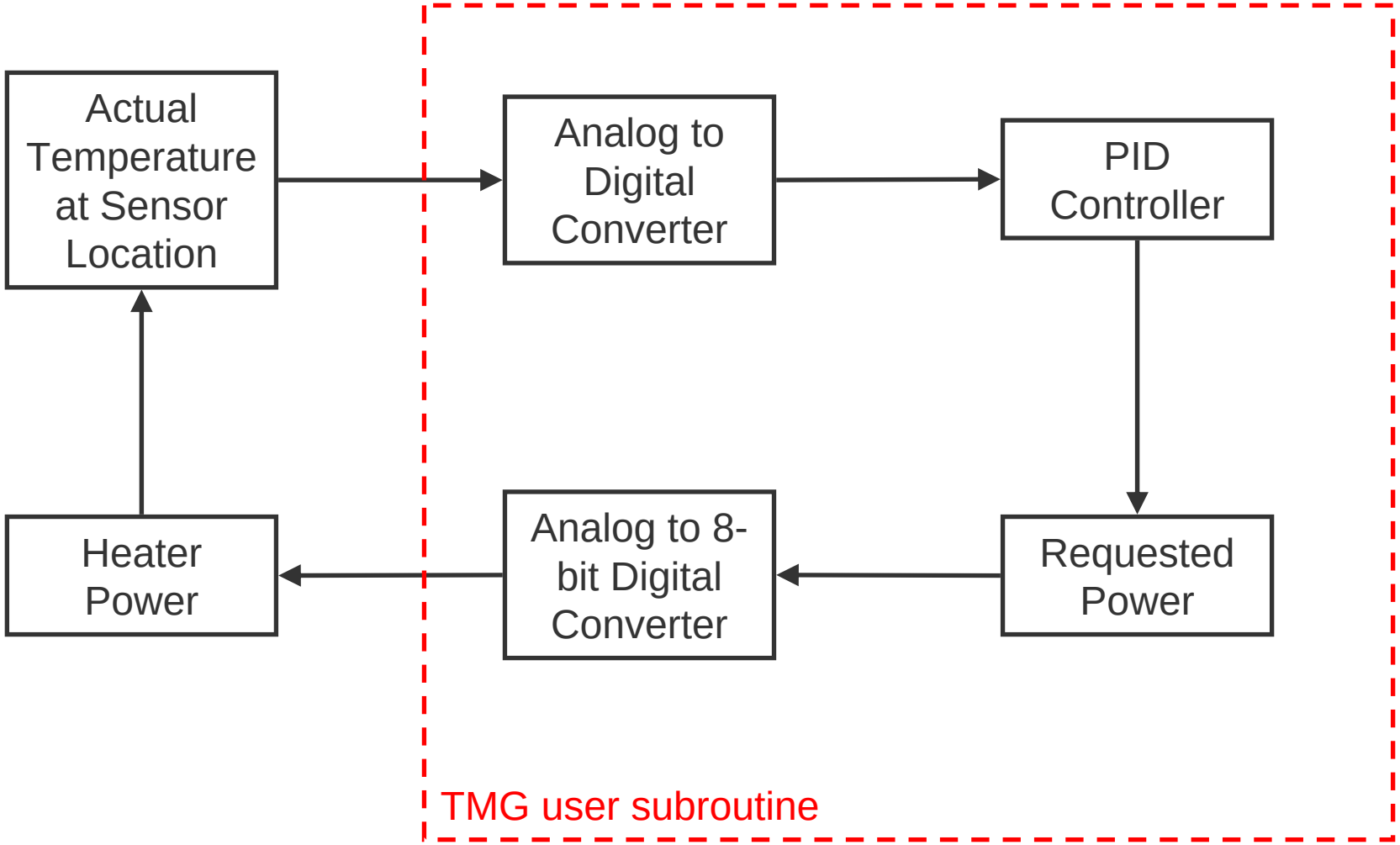
Solution Schematic



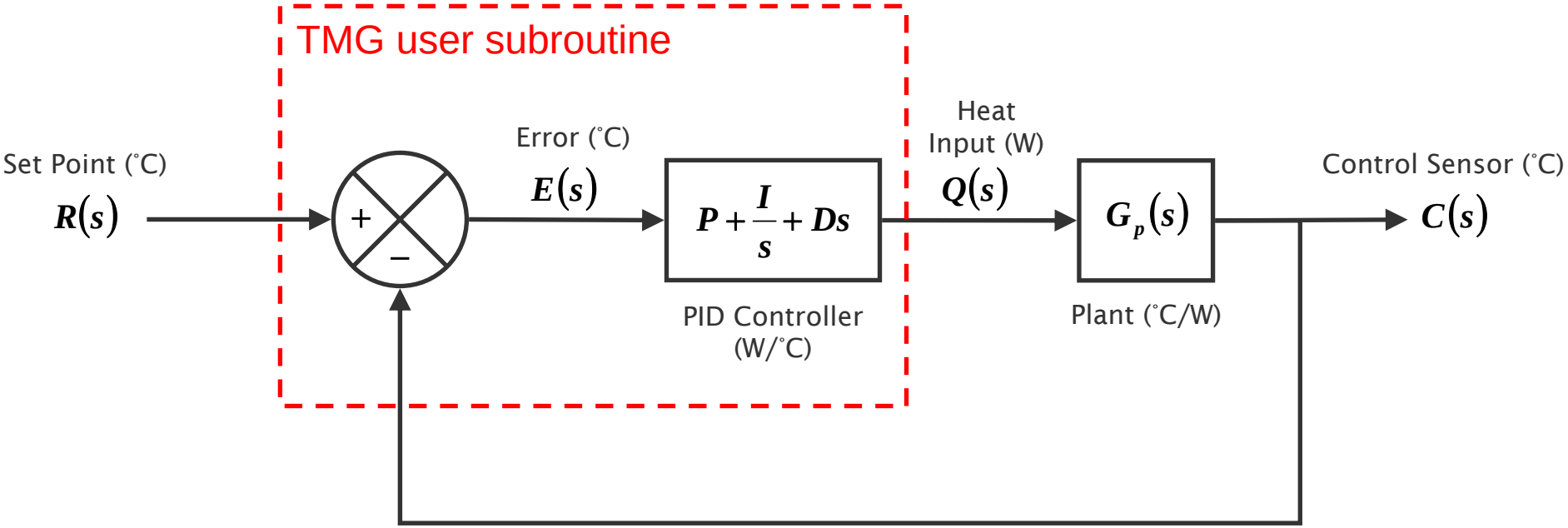
Actual Control System



TMG Control System Simulation

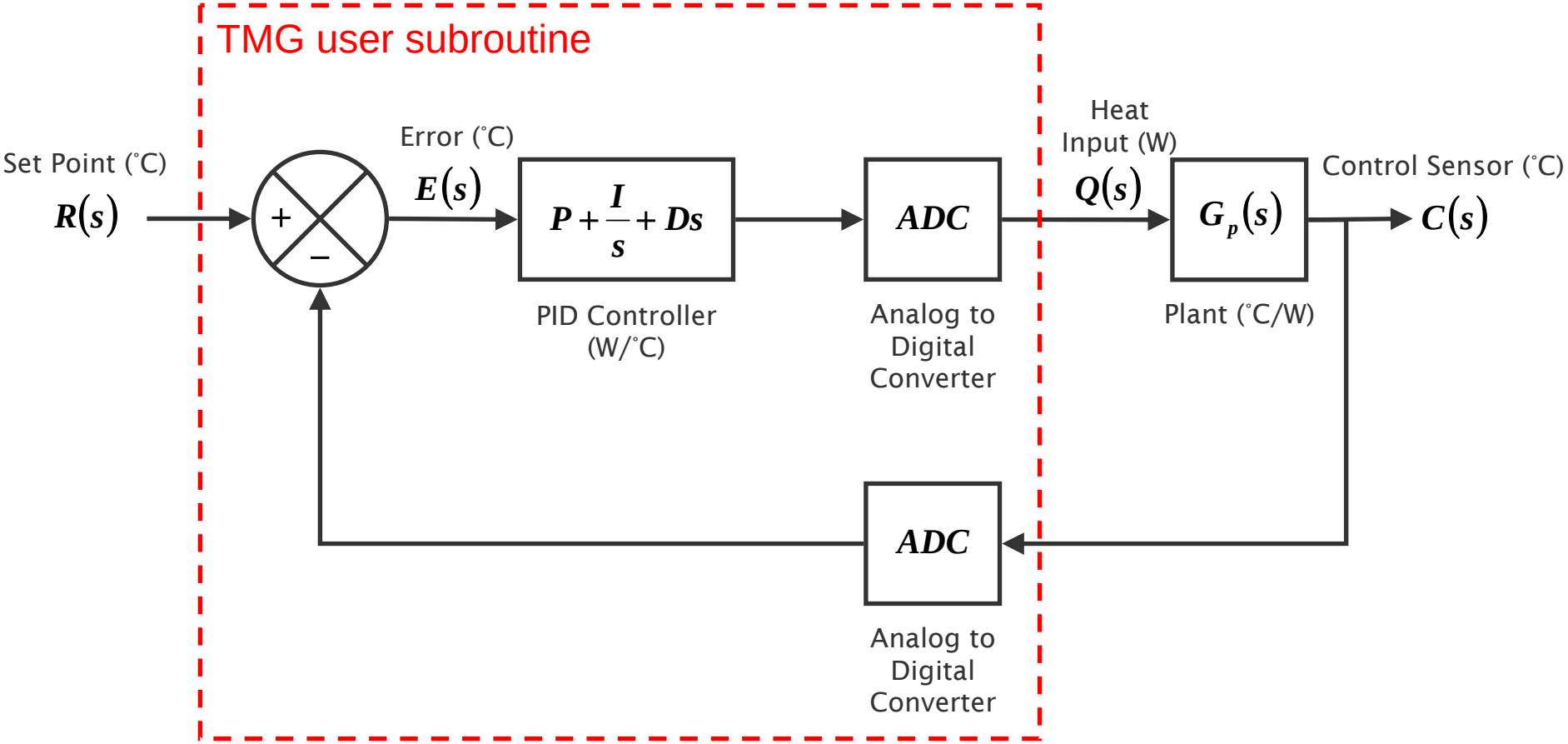


Control System Block Diagram



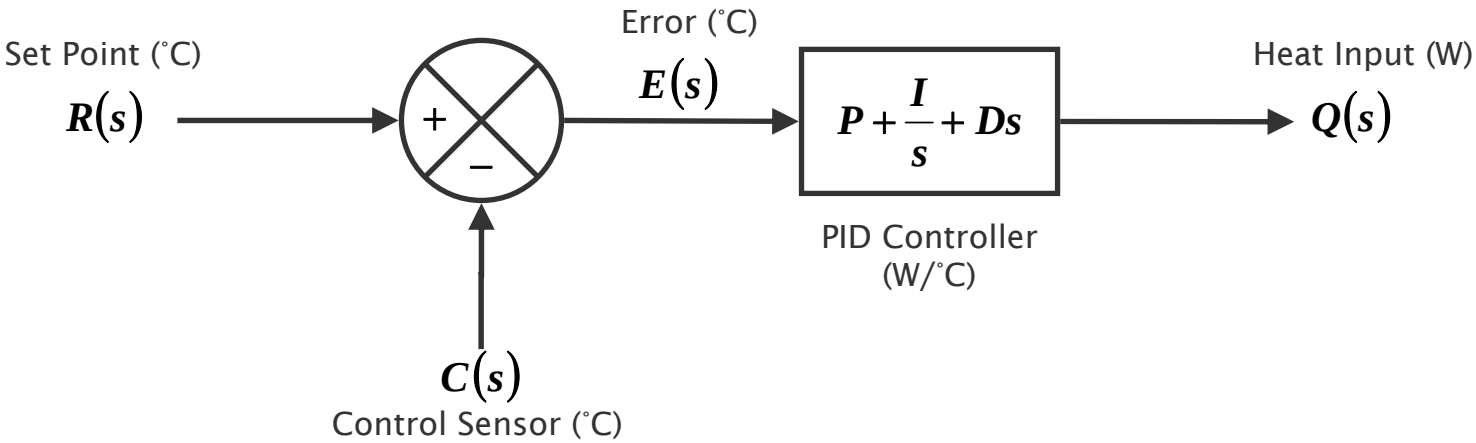
Analog Control

Control System Block Diagram



Digital Control

Control System Equations



Laplace Domain

$$R(s) - C(s) = E(s)$$

$$\left(P + \frac{I}{s} + Ds\right)E(s) = Q(s)$$

Time Domain

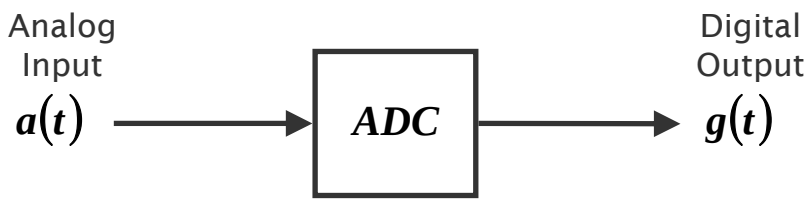
$$r(t) - c(t) = e(t)$$

$$Pe(t) + I\int_0^t e(\tau)d\tau + D\frac{de}{dt} = q(t)$$

PID Interpretation

$$q(t) = \underbrace{Pe(t)}_{\text{Compensation based on the current error value}} + \underbrace{I\int_0^t e(\tau)d\tau}_{\text{Compensation based on the history of the error value}} + \underbrace{D\frac{de}{dt}}_{\text{Compensation based on future predictions for the error value}}$$

Analog to Digital Equations



Valid linearly spaced digital outputs are given by

$$g(t) = g_0 + n\delta$$

where n is an integer and δ is the digital increment.

The analog to digital conversion equation is

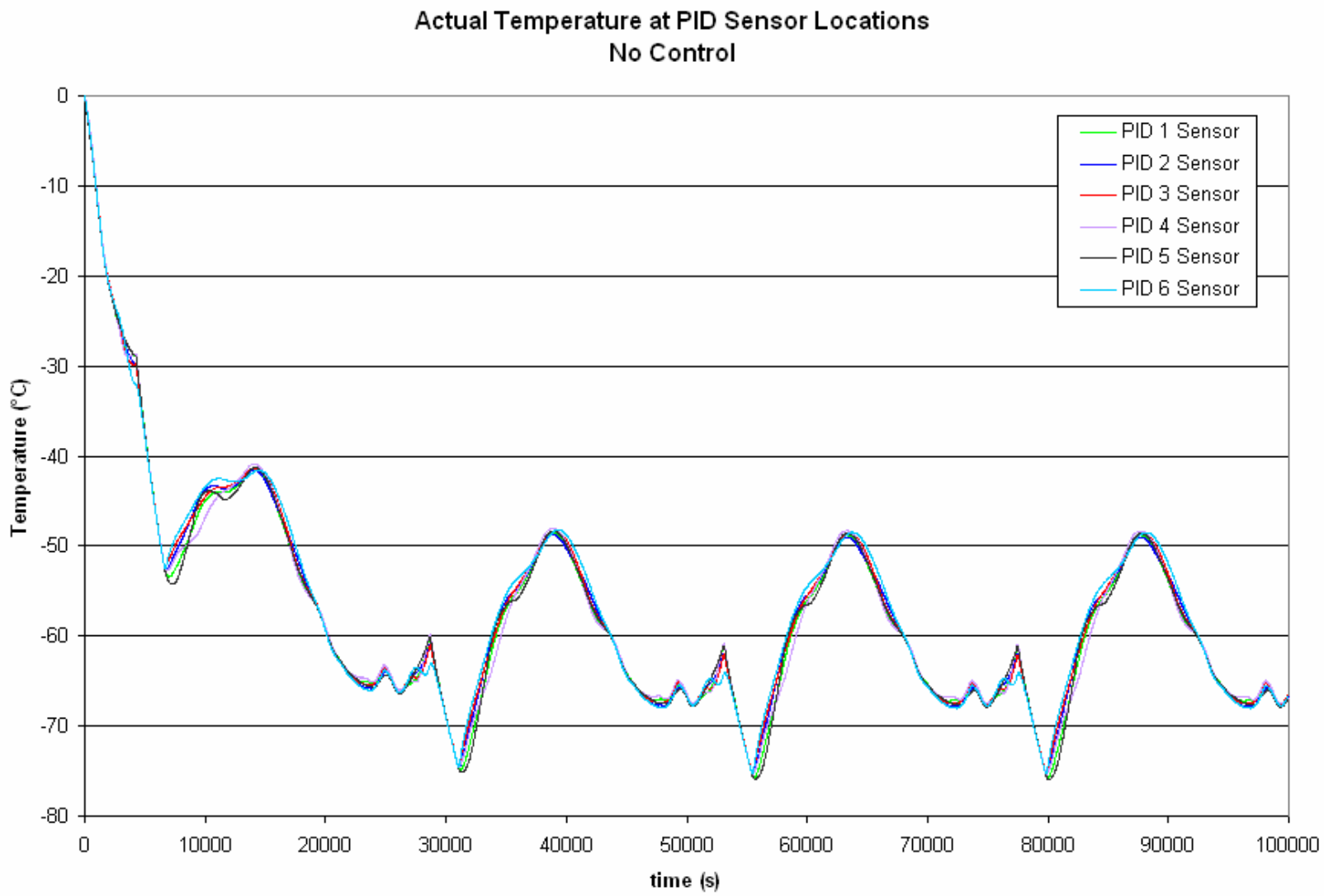
$$g(t) = g_0 + \delta\,\mathrm{int}\left(\frac{a(t) - g_0}{\delta} + \frac{1}{2}\right)$$

where int(x) is the greatest integer function (returns the largest integer that is less than x).

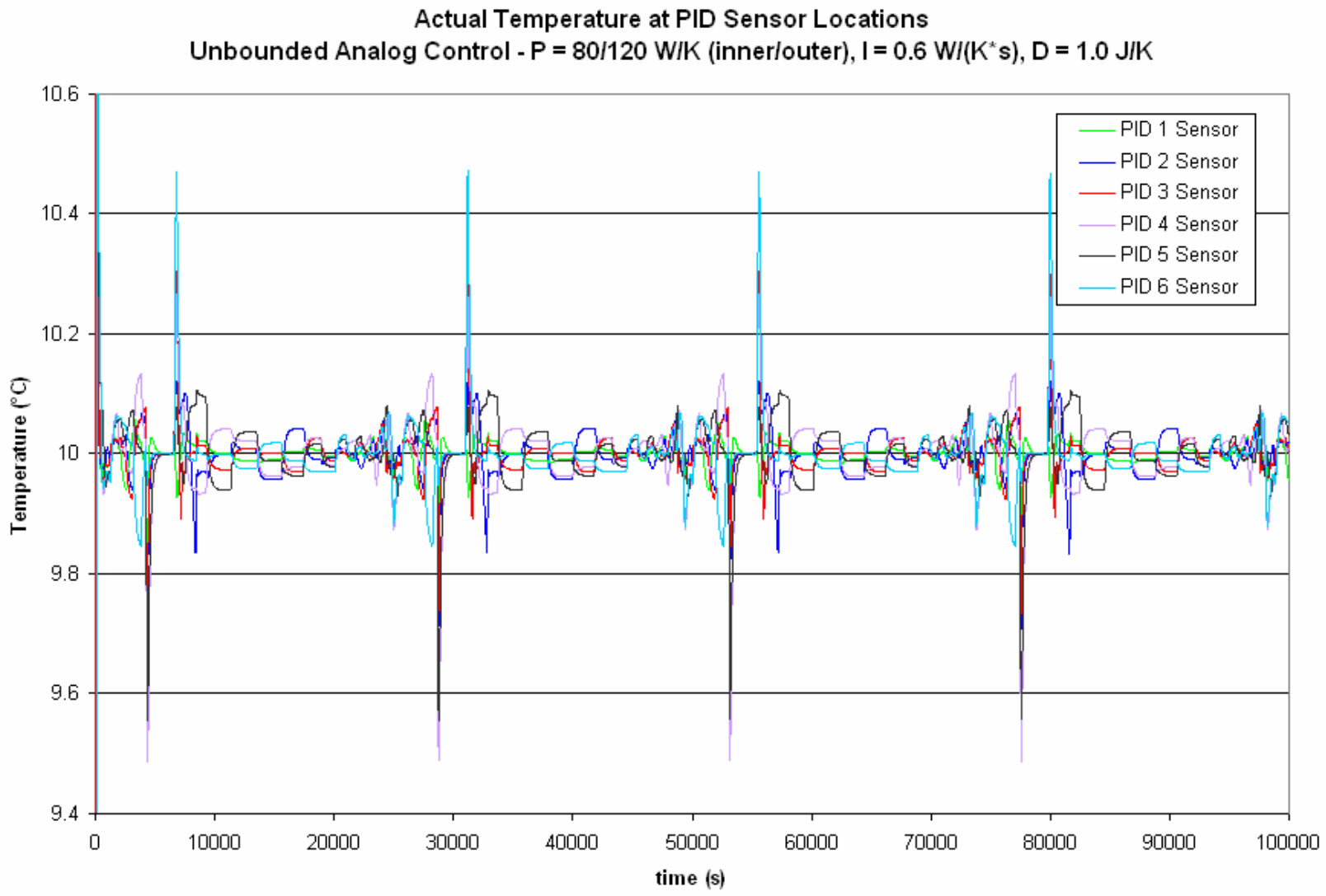
Sensor Sampling Rate

- In order to model the sampling rate of the temperature sensor, the time step for the transient solution should be set to the sampling rate of the temperature sensor.
- This method makes the following assumptions:
  - There is no lag in the temperature sensor.
  - The PID power is computed and applied to the system instantaneously.
  - PID power is held constant from one sample time to the next.

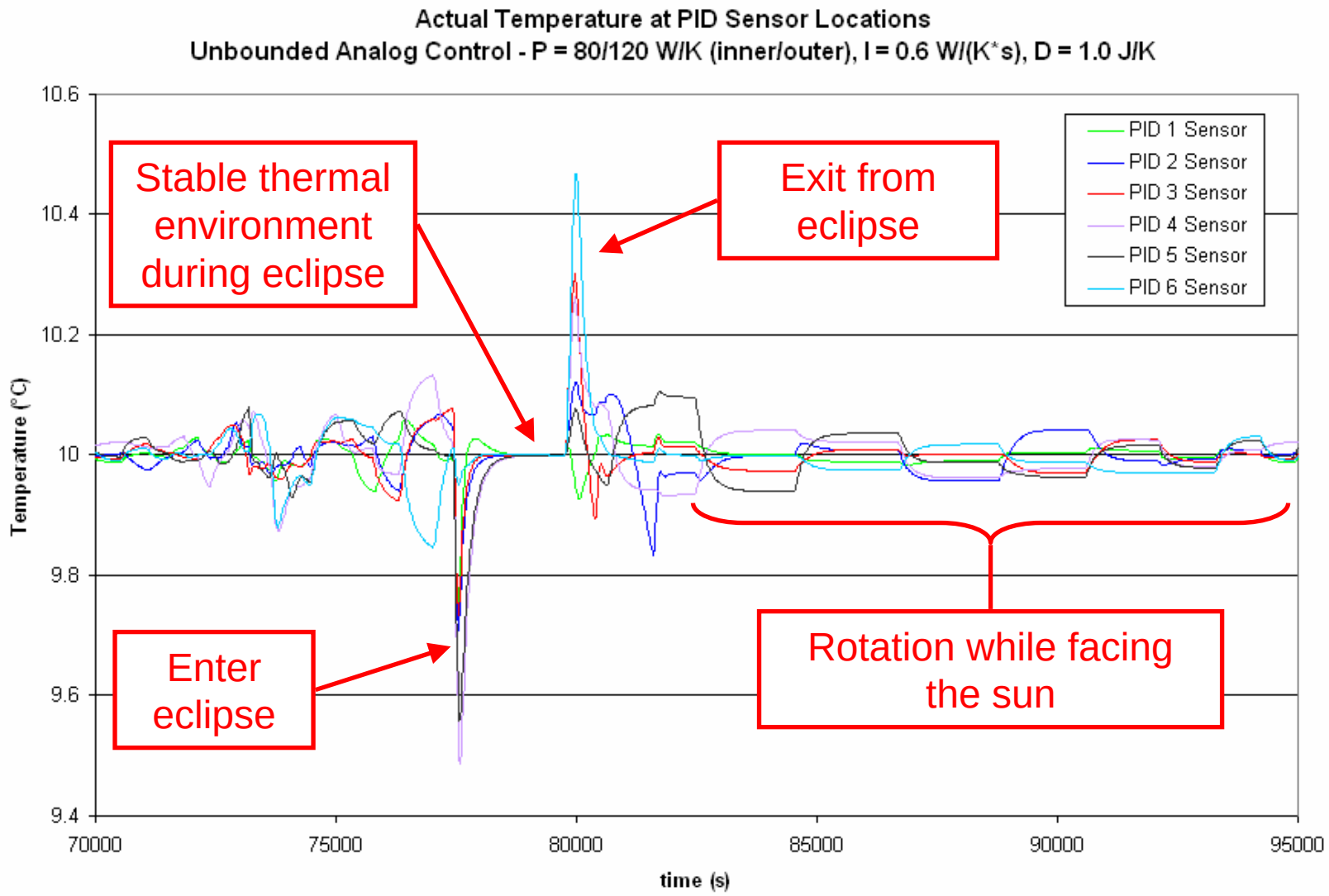
Temperature Results – Heaters Off



Temperature Results – Analog



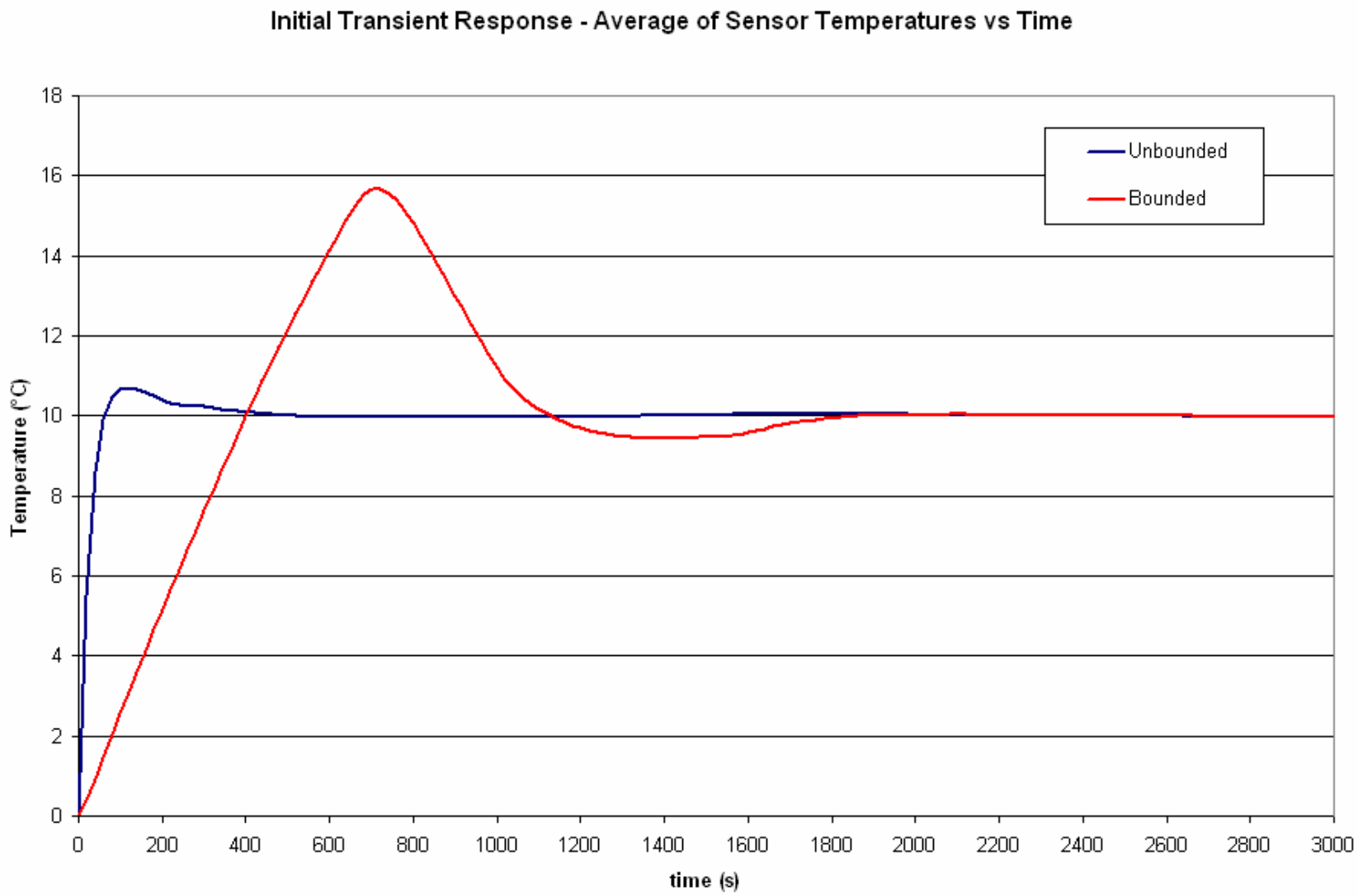
Temperature Results – Analog



Real World PID

- Based on the error, the PID controller can request any amount of power from the heater.
- However, the heater cannot accommodate every possible request made by the PID controller.
  - Actual heater power cannot be negative.
  - The actual heater has a maximum output.
- In order to simulate the actual heater performance, the heater output must be bounded by maximum and minimum allowable power values.
- Bounded heater power most significantly effects the initial response of the system at startup.

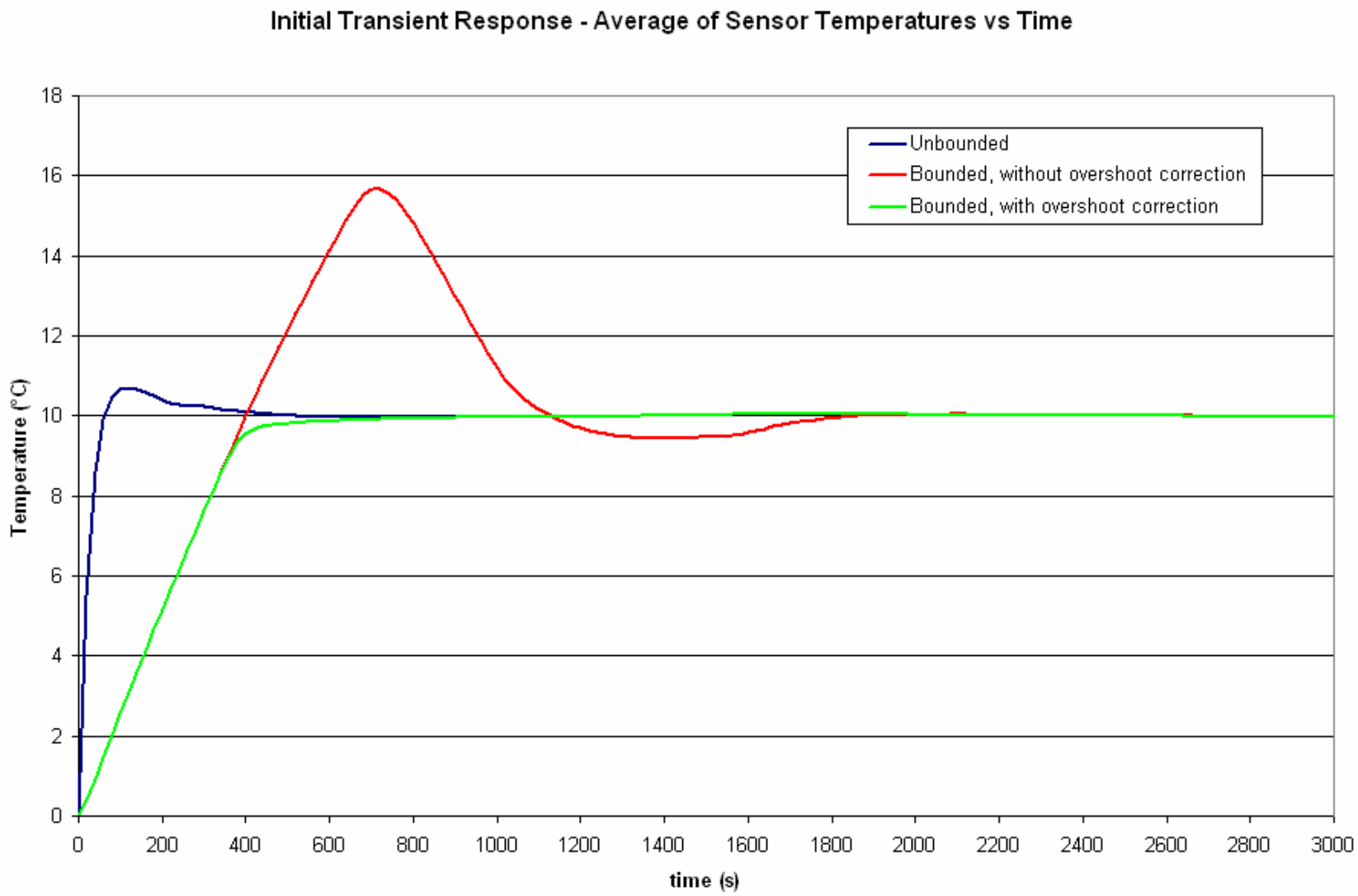
Initial Transient Response – Bounded vs. Unbounded Heater Power



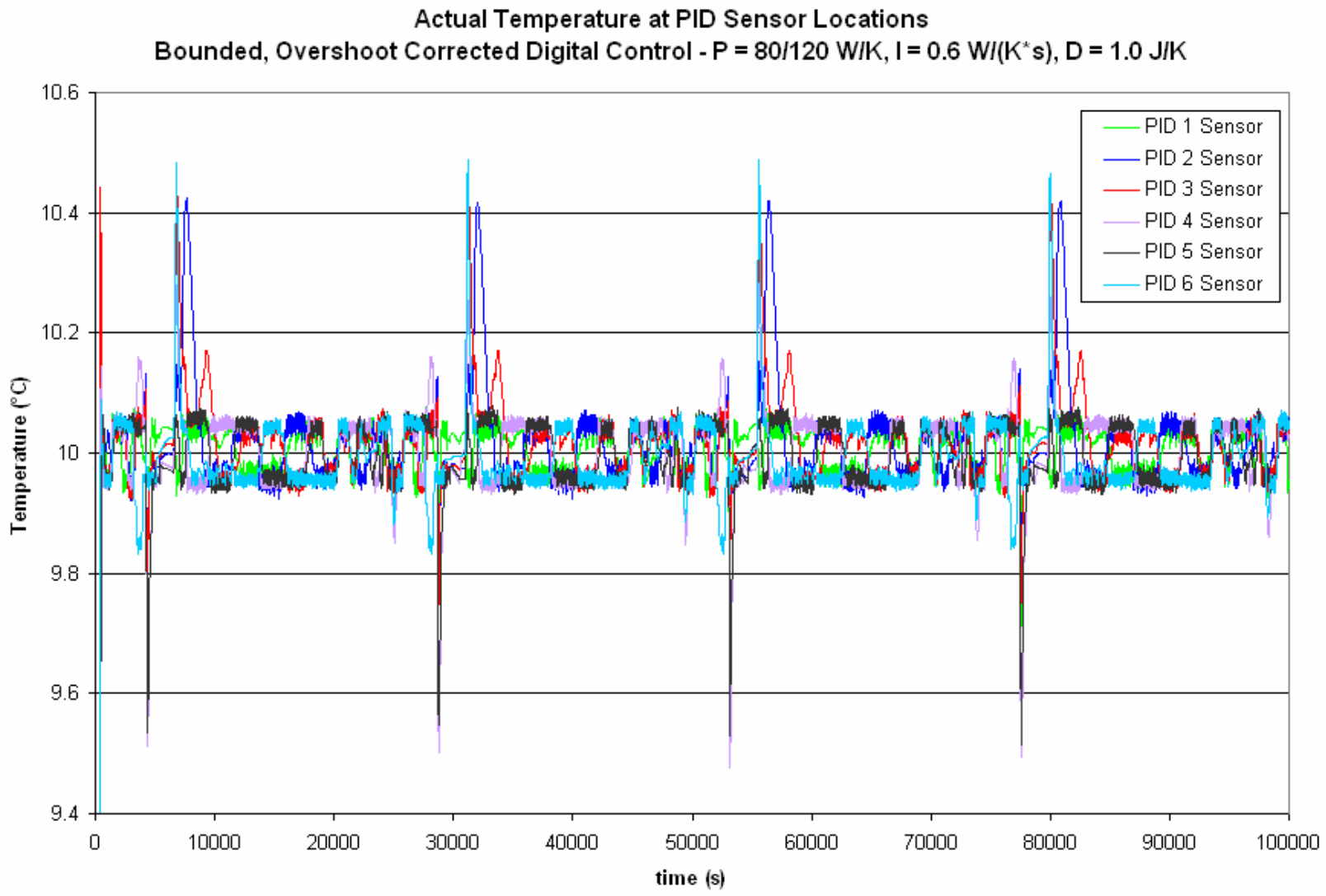
Why Did the Bounded Case Overshoot So Much?

- From time 0-400s, the heater is at maximum power, but it still takes time to reach the set point temperature.
- During this time, the error integral builds up and continues to ask for high power after the set point is reached. This causes large overshoot.
- A way to correct for this is to freeze the error integration (do not allow it to change) whenever the requested power is out of range. Maximum or minimum power is still applied to the system as long as it is needed, but the integral term does not build up and cause large overshoot.

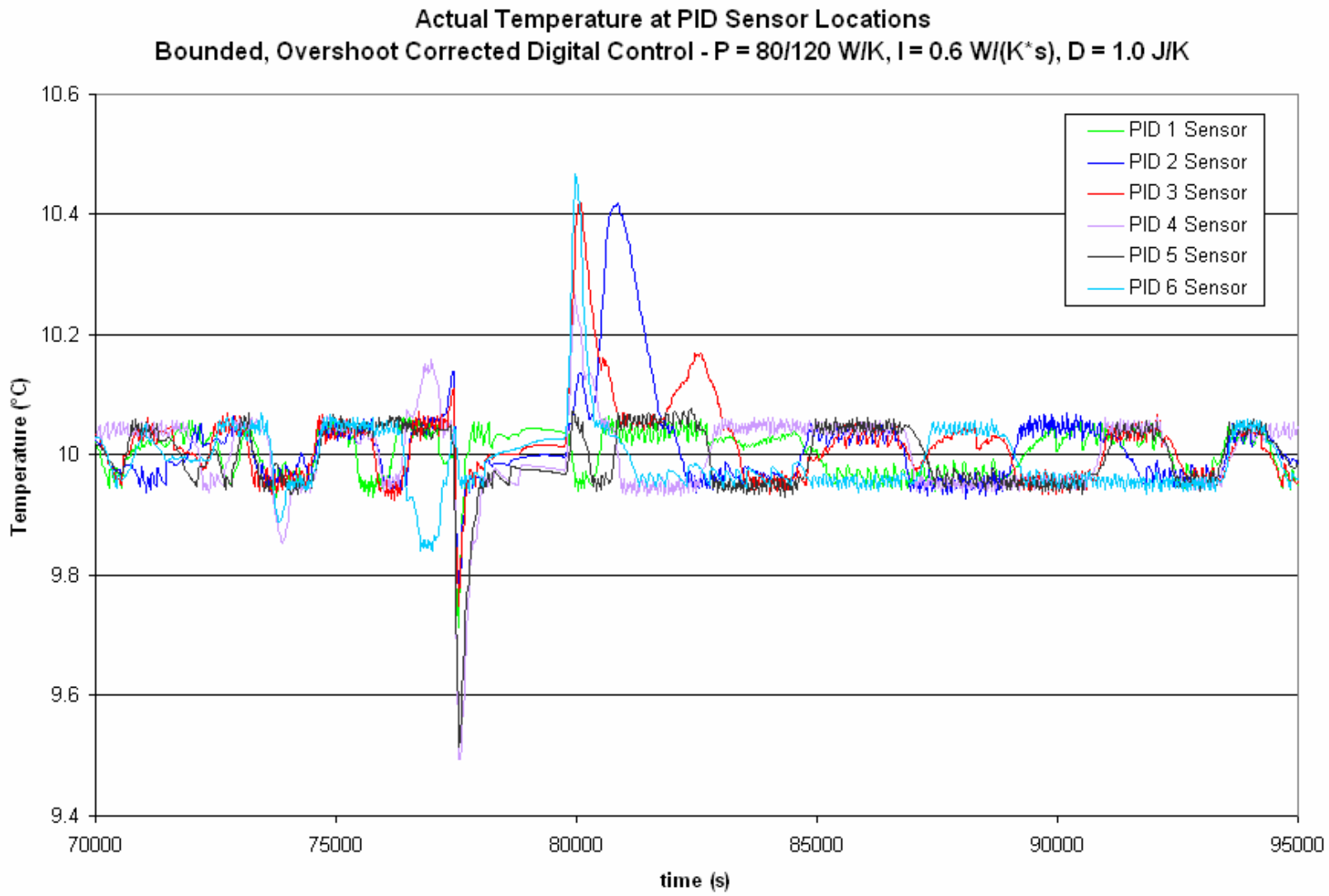
Initial Transient Response – Bounded Heater Power with Overshoot Correction



Temperature Results – Digital



Temperature Results – Digital (detail)



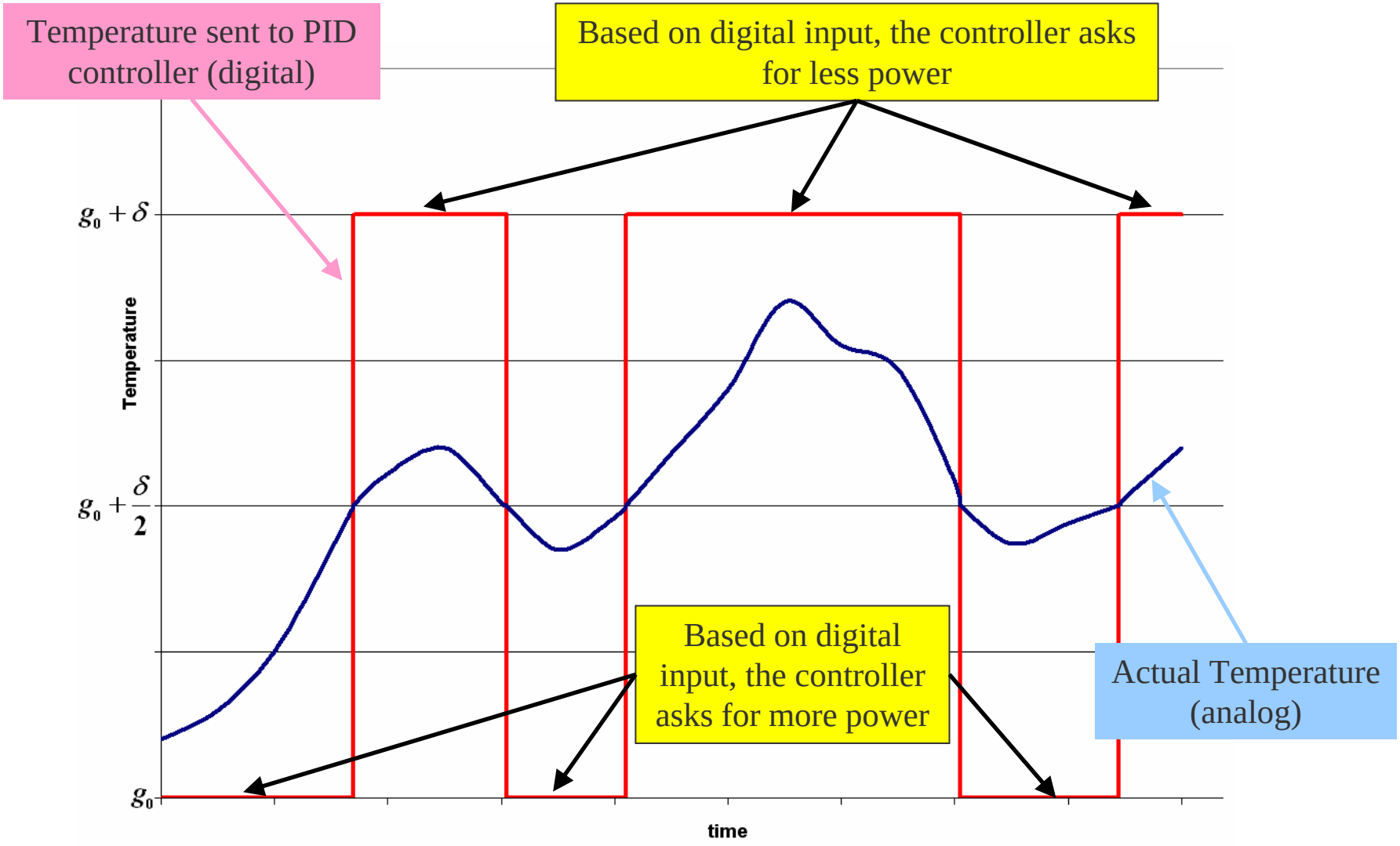
Comparison of Results – Analog vs. Digital

- The analog and digital responses are qualitatively similar and show approximately the same maximum and minimum temperatures at most of the control sensor locations, but a few of the sensors show larger fluctuations in the digital case.
- The digital response tends to exhibit high frequency fluctuations at the digital threshold locations (half way between digital output temperatures).

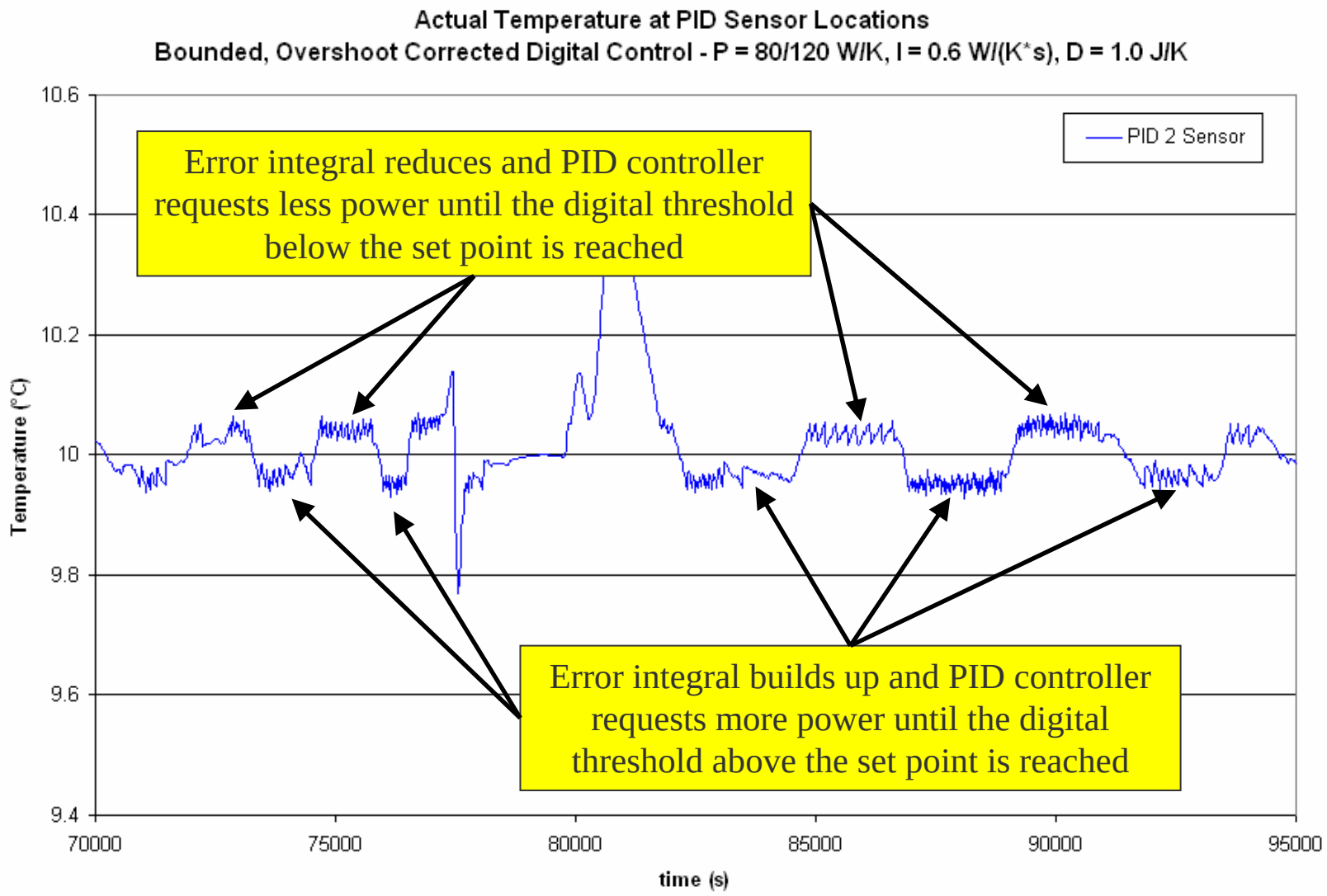
Comparison of Results – Analog vs. Digital

- The digital response also shows low frequency fluctuation between the threshold values above and below the set point temperature.

High Frequency Fluctuation Around Digital Threshold Values



Low Frequency Fluctuation Between Digital Threshold Values



Conclusions

- In cases where the digital step size is not insignificant compared to the control range, digital response should be modeled to achieve accurate response predictions.
- A user-written subroutine that interfaces with the TMG thermal solver offers the flexibility to model real world behavior of PID controllers including digital temperatures and/or digitally controlled heaters.

Acknowledgements

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