Dynamical systems modelling (Transfer functions, state space models)

Control System Toolbox for transfer functions and state space models !

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Why is Control Necessary?

There are two main reasons for control.

The first reason for control is to maintain the controlled variable at its desired value when disturbances occur.

The second reason for control is to respond to changes in the "desired value".

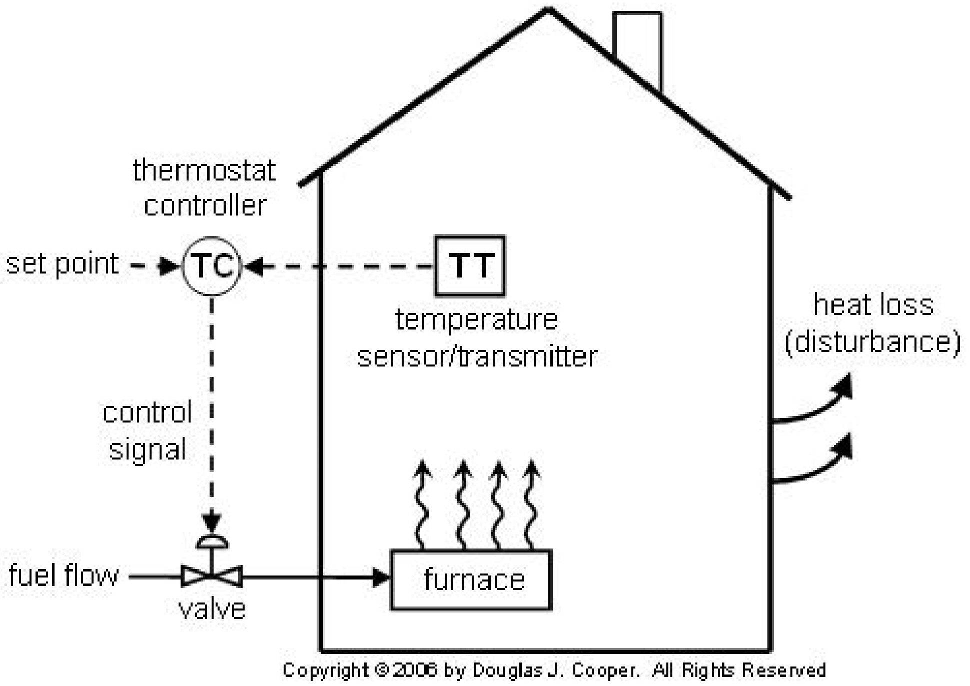
What does a control system do?

Maintain desired conditions in a physical system by adjusting selected variables.

- A specific value or range is used as a desired value for the controlled variable.
- The conditions of the system are measured.
- Each system has a control calculation or algorithm.
- The results of calculation are implemented by final control elements.

Control Objectives

1. Safety
2. Environmental Protection
3. Equipment Protection
4. Smooth Operation and Production Rate
5. Product Quality
6. Profit
7. Monitoring and Diagnosis



1 Control objective:

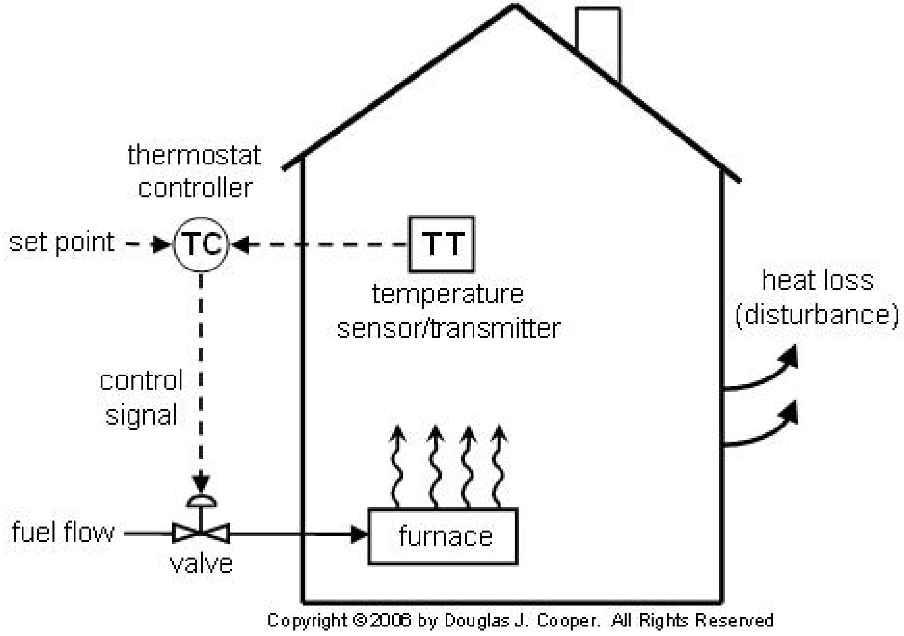
Consider a house in a cold climate which is to be maintained near a desired temperature by circulating hot water through a heat exchanger.

2 Input and output variables:

Heated room example: input: fuel to the furnace
output: room temperature

3 Constrains: operating characteristics

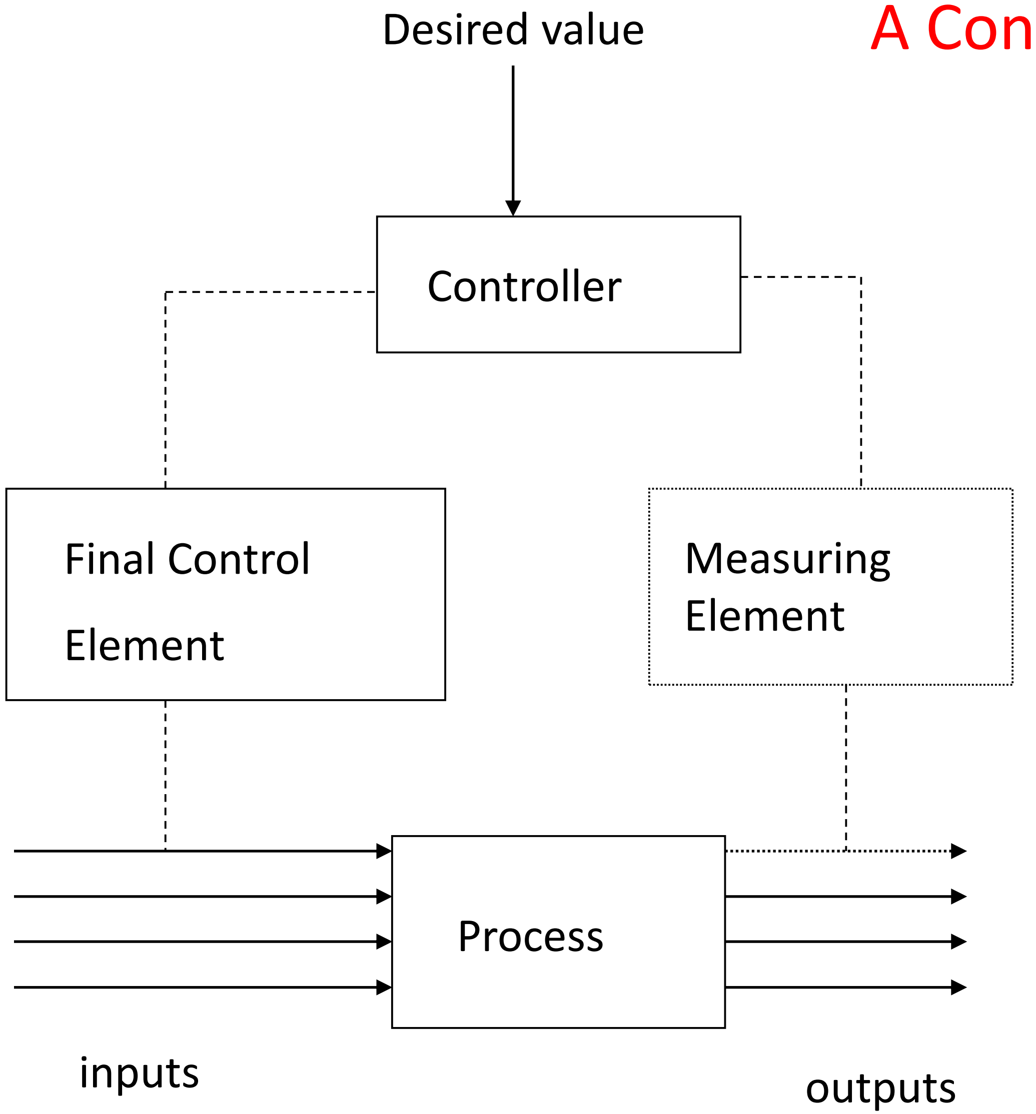
We assume, for example, that the valve operates between the extremes of fully closed or fully open, and that the system operates continuously.



4 Safety, environmental and economic considerations

5 Control structure

- Temperaturere of the room is determined by a thermostat.
- This temperature is compared with the desired temperature or range of temperatures.
- If the temperature is below than the desired value, the furnace and the pump are turned on; if the temperature is above, the furnace and pump are turned off.



A Control Engineering "Engineer" is in charge of

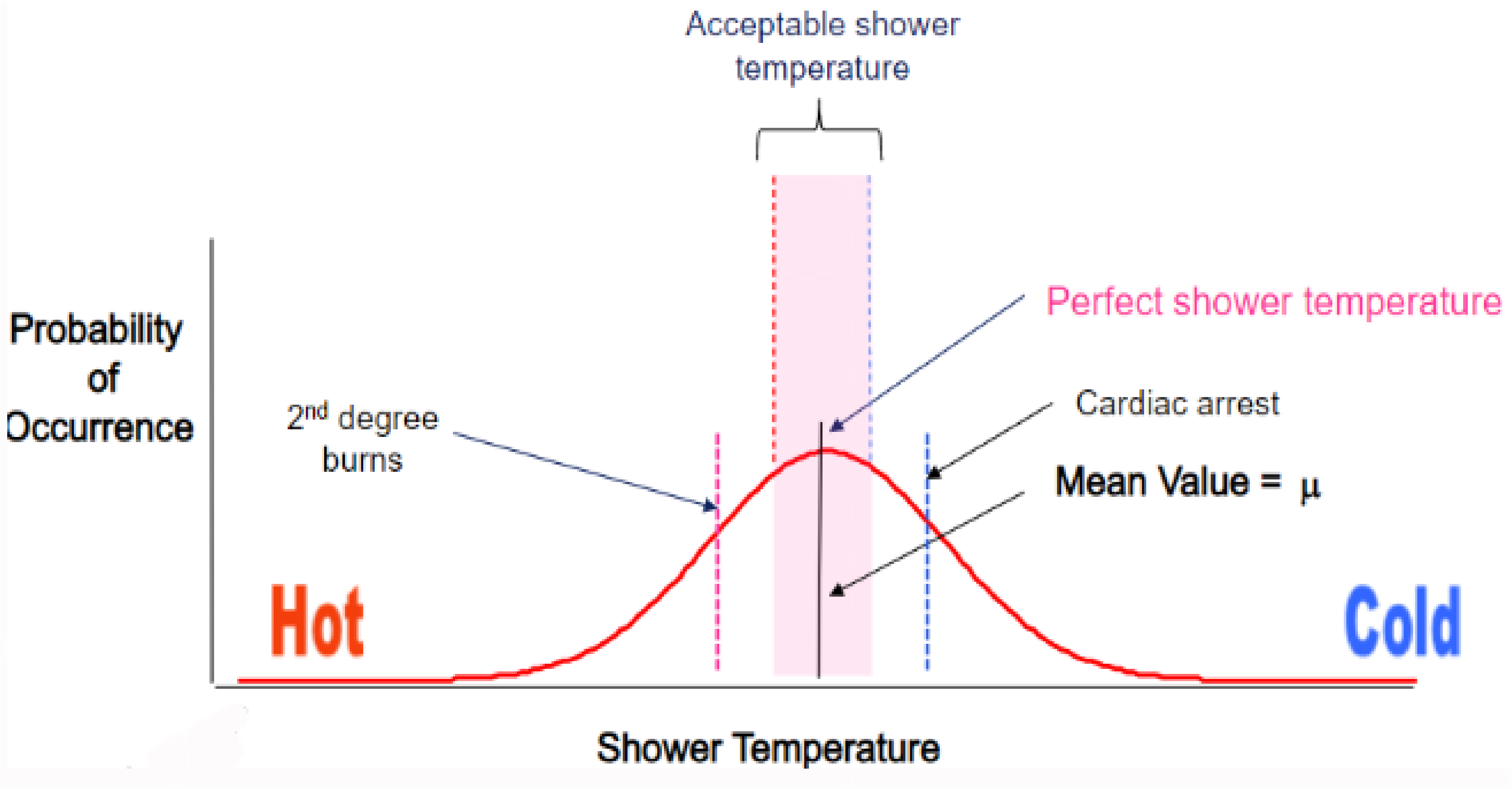
1. Process Design
2. Measurements
3. Final Control Elements
4. Control Structure
5. Control Calculations

Behavior of System Variables

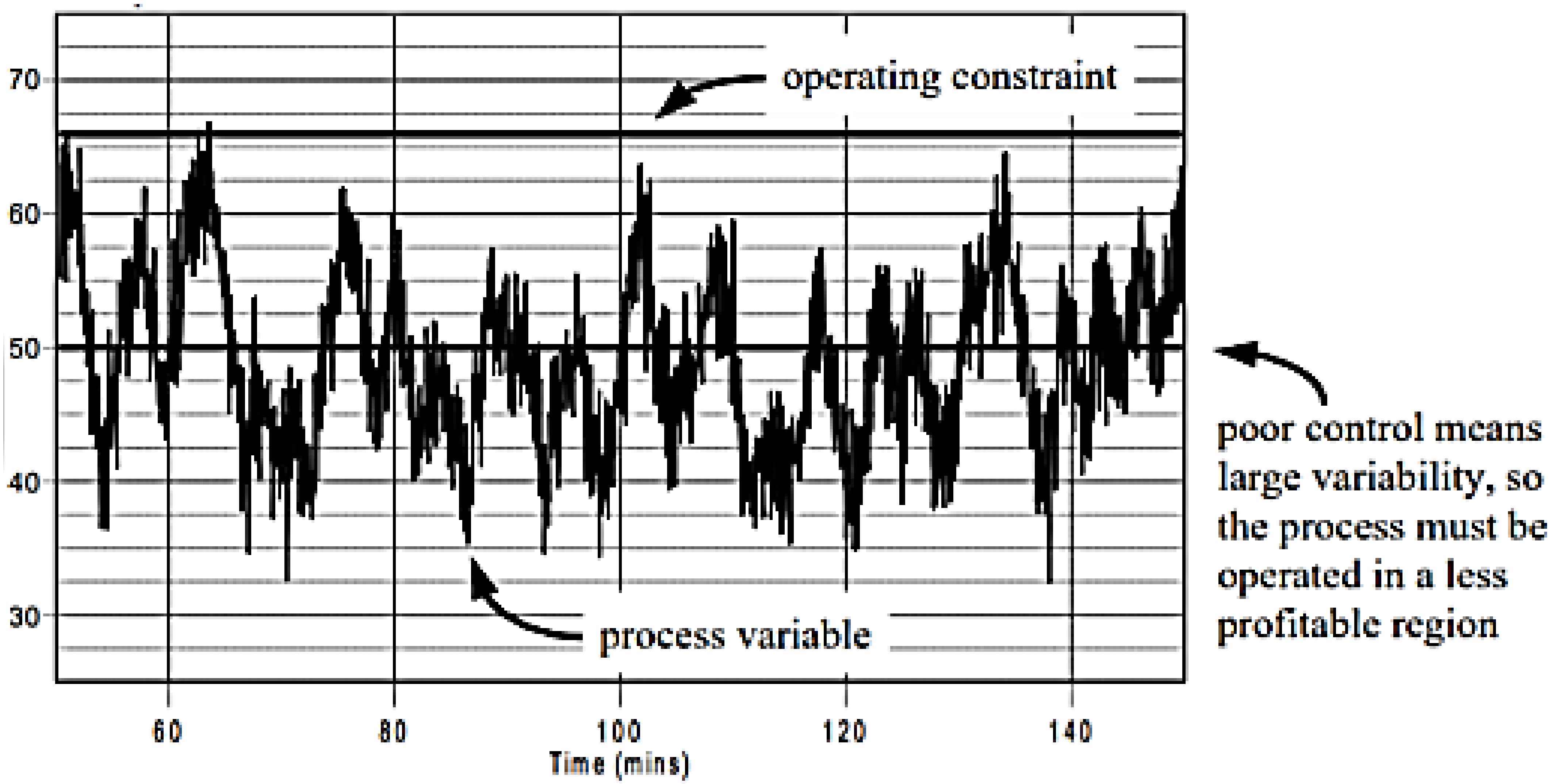
1. In process control two types of variables exist:
   i. Manipulated variables, which can be adjusted
   ii. Controlled variables, which are affected by the adjustments.
2. There is a specified range for the variables.
3. The effectiveness of control to maintain the process at desired conditions depends on:
   i. Sign and magnitude of response
   ii. Speed of response
   iii. Shape of response
4. The analysis of the system possible variations, and sensitivity of the dynamic behavior to those variations are important in the modeling.

Steady-State System Response

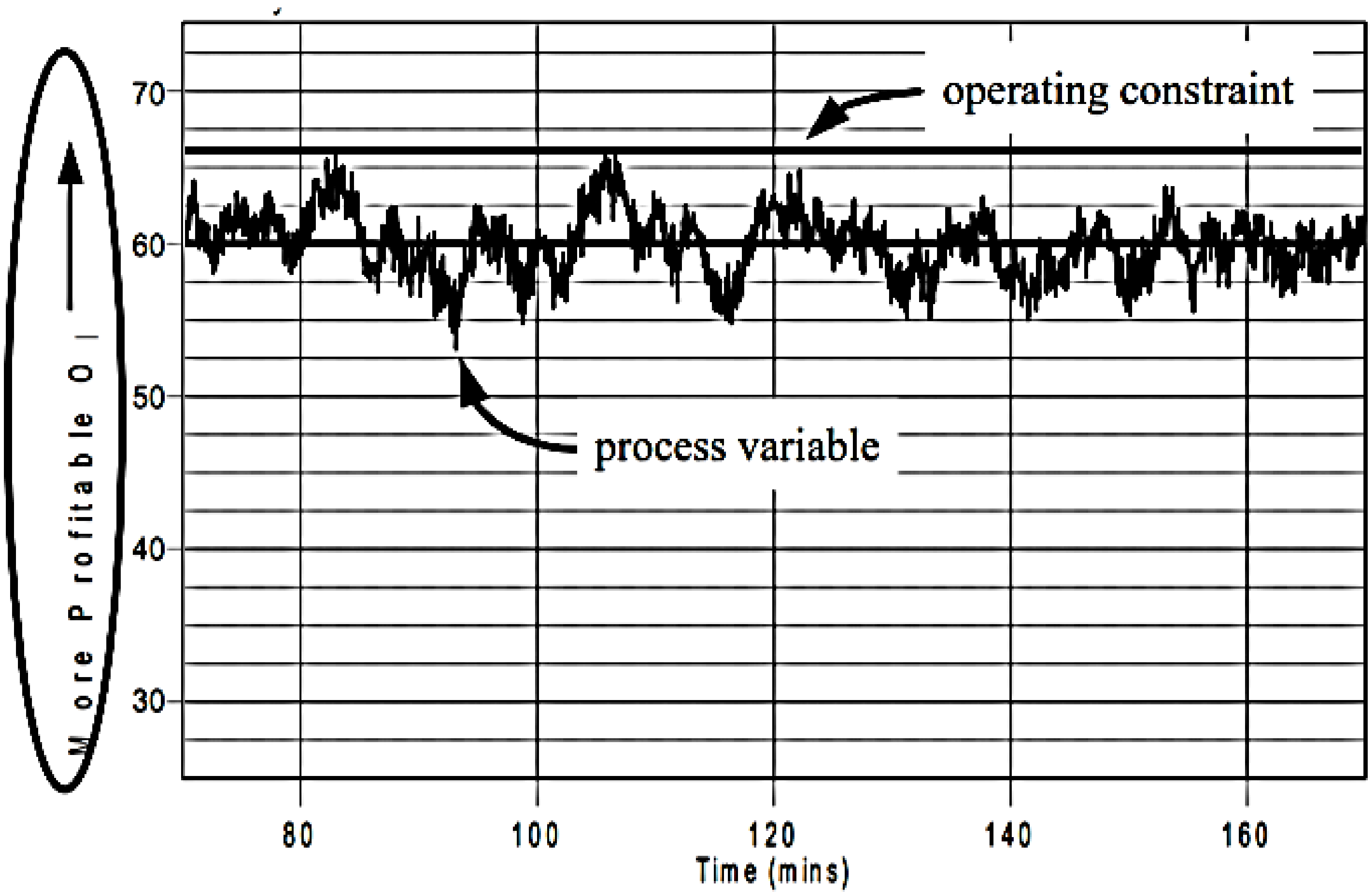
Objective: to reduce variability in the control loop



Poor Control-large variability

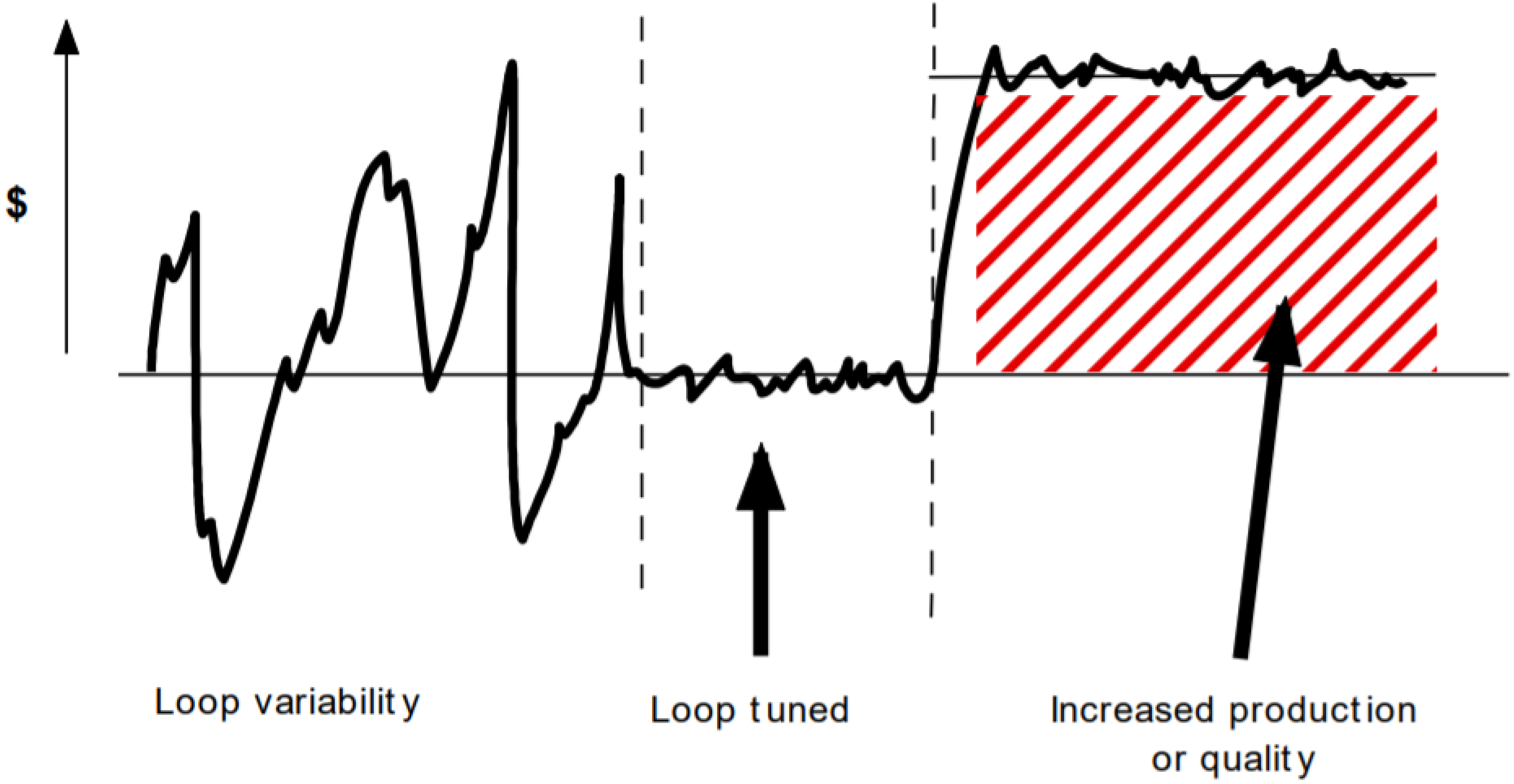


Tight control – less waste-more profit

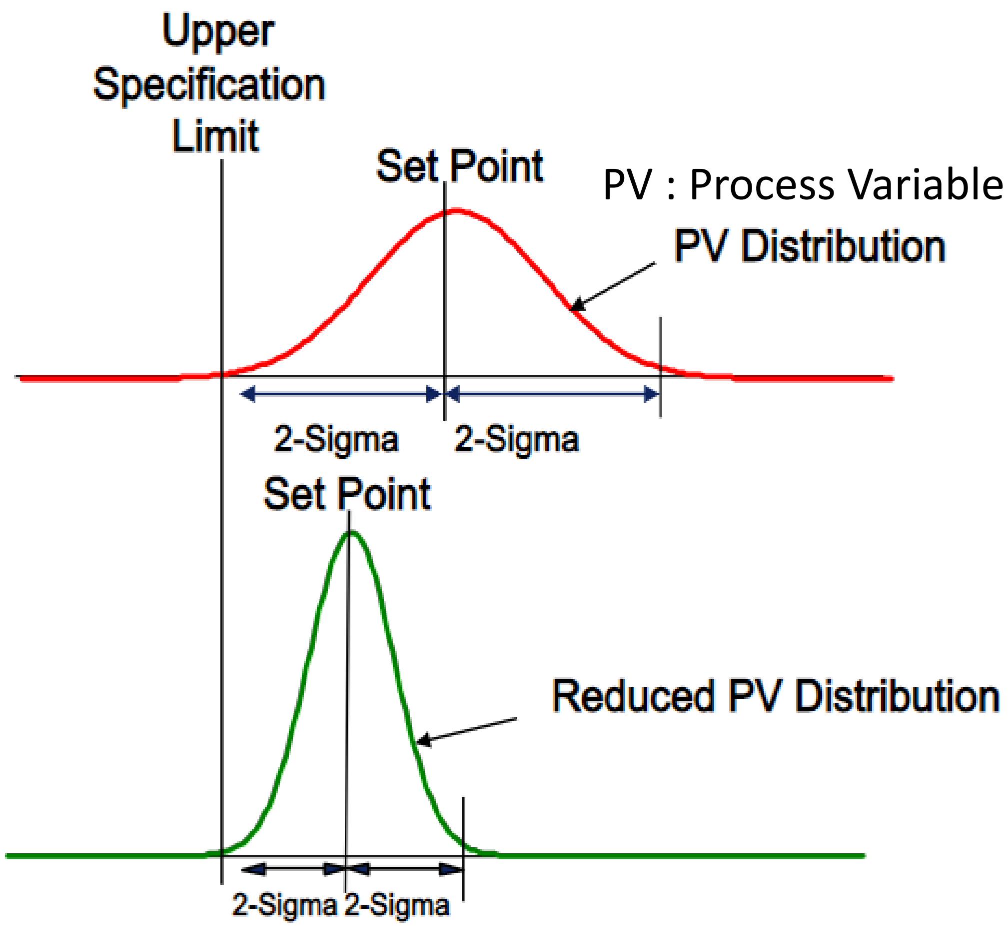


tight control permits operation near the constraint, which means more profit

Objective: to reduce variability in the control loop



Objective: to reduce variability in the control loop



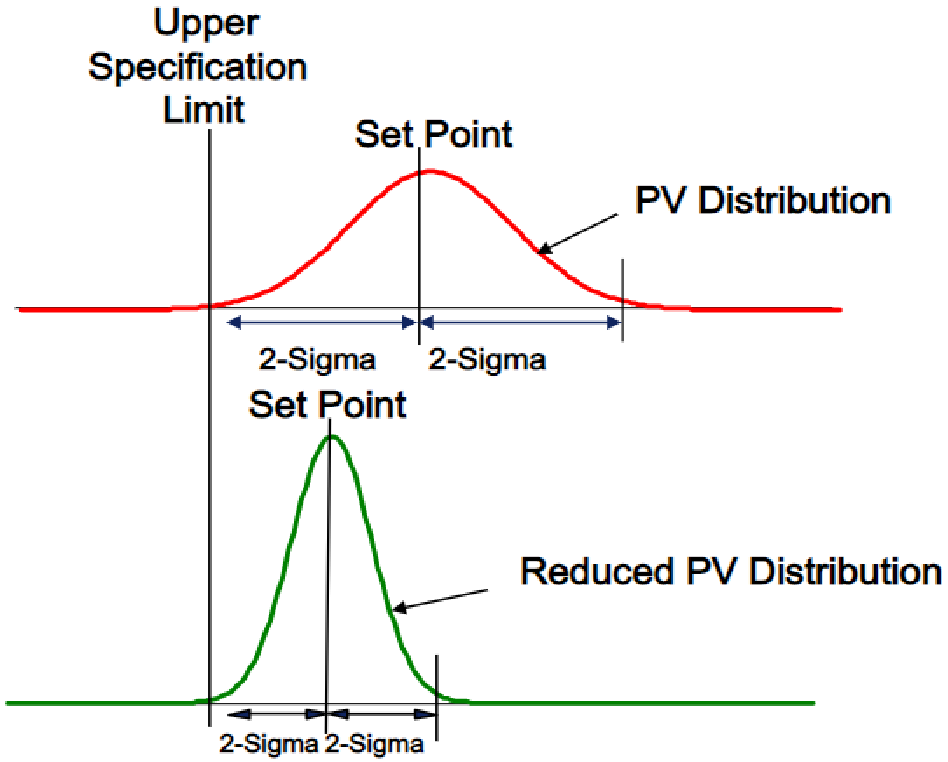
The normal distribution or Gaussian distribution

The usual justification for using the normal distribution for modeling is the **Central Limit theorem**, which states (roughly) that the sum of independent samples from any distribution with finite mean and variance converges to the normal distribution as the sample size goes to infinity.

Statistics and Machine Learning Toolbox™ offers several ways to work with the normal distribution.

https://www.mathworks.com/help/stats/normal-distribution.html

Objective: to reduce variability in the control loop



The standard normal distribution has zero mean μ and unit standard deviation.

If z is standard normal, then $\sigma z + \mu$ is also normal with mean μ and standard deviation σ.

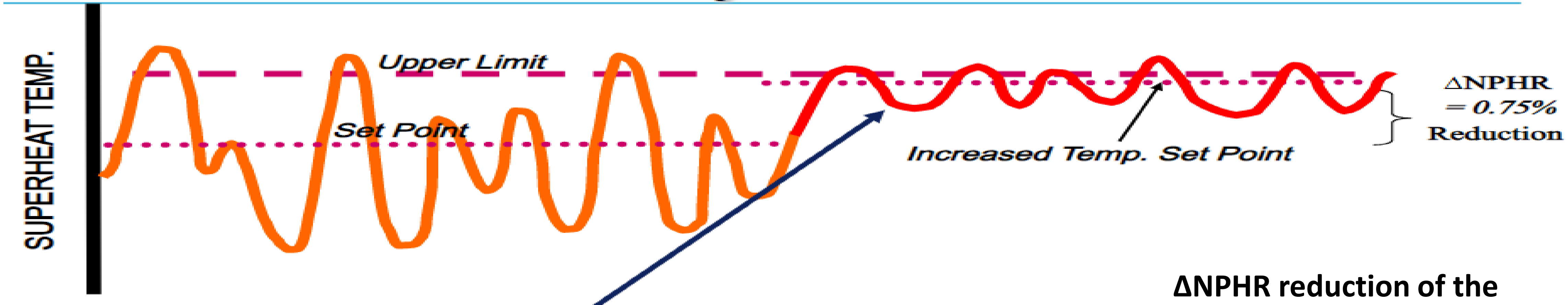
Parameters

The normal distribution uses these parameters.

Parameter	Description	Support
mu (μ)	Mean	$-\infty < \mu < \infty$
sigma (σ)	Standard deviation	$\sigma \geq 0$

https://www.mathworks.com/help/stats/normal-distribution.html

Main Steam Temperature Control
Decreased Variability = Increased Profit



Reduced Process Variability Provides the Opportunity for Setpoint Change

ΔNPHR reduction of the set point variability

$$\text{Savings} = \underbrace{\left(\frac{0.75}{100}\right)}_{\text{Reduction}} \underbrace{\left(11000\ \frac{\cancel{BTU}}{\cancel{KW\cdot HR}}\right)\left(\frac{\$\,6.563}{MM\ \cancel{BTU}}\right)}_{\text{gas cost}} \underbrace{\left(320000\ \cancel{KW}\right)}_{\text{consumption}} \underbrace{\left(8760\ \frac{\cancel{HR}}{\text{Year}}\right)}_{\text{time}}$$

BTU: British gas units

MM = 1000000

$$\text{Savings} = 1'517.785\ \frac{\$}{\text{year}}$$

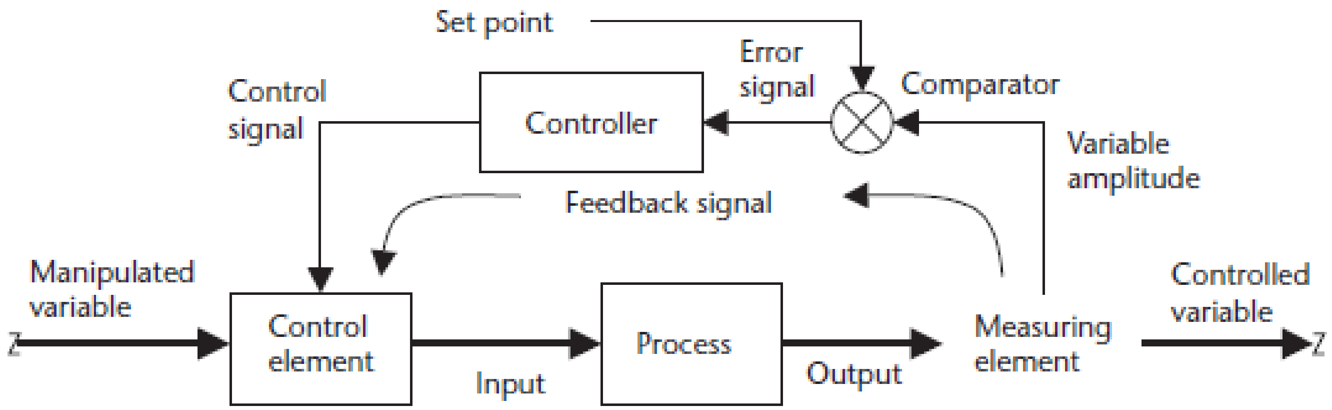
Elements in a Control Loop

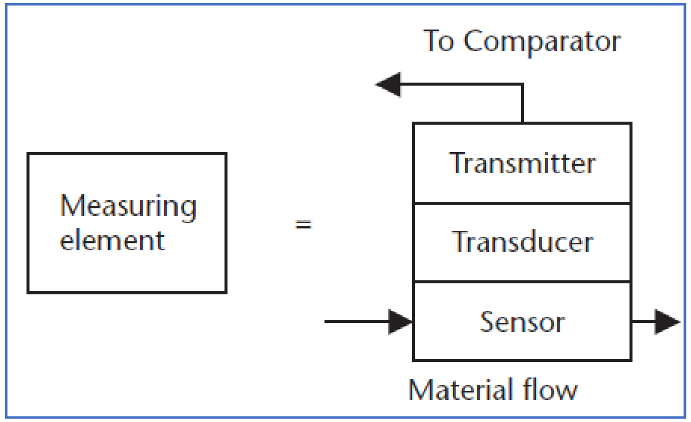
Measurements

"One can control only what is measured"

Measurement is the determination of the physical amplitude; the measurement value must be consistent and repeatable.

The engineer should select sensors that measure important variables rapidly, reliably and with sufficient accuracy.

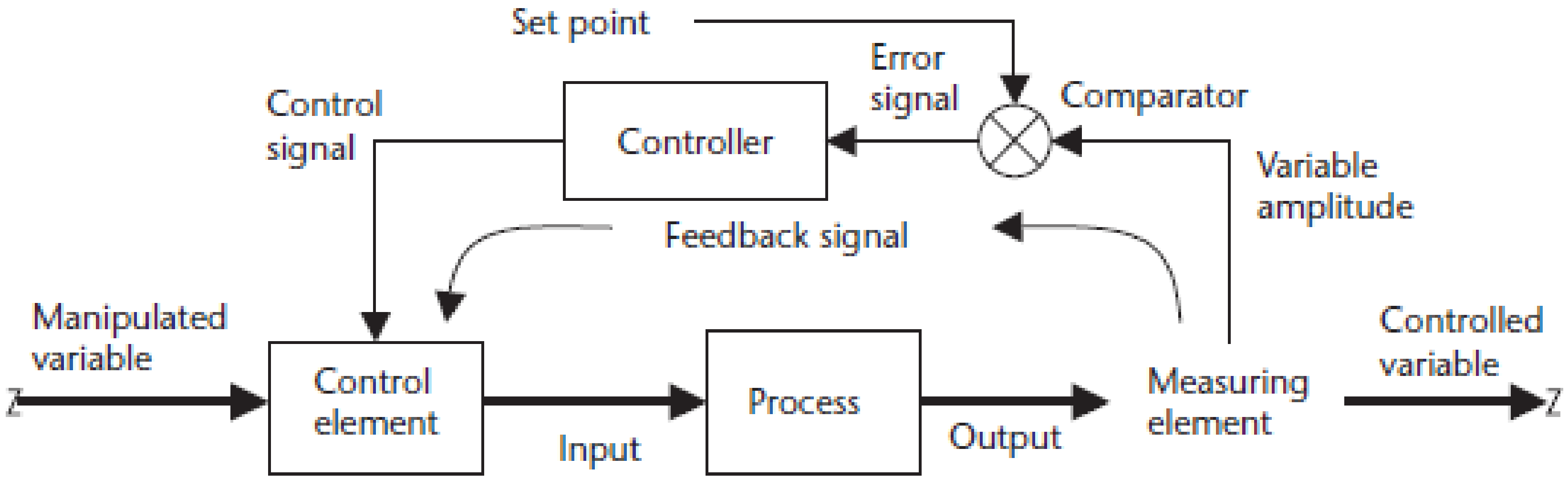


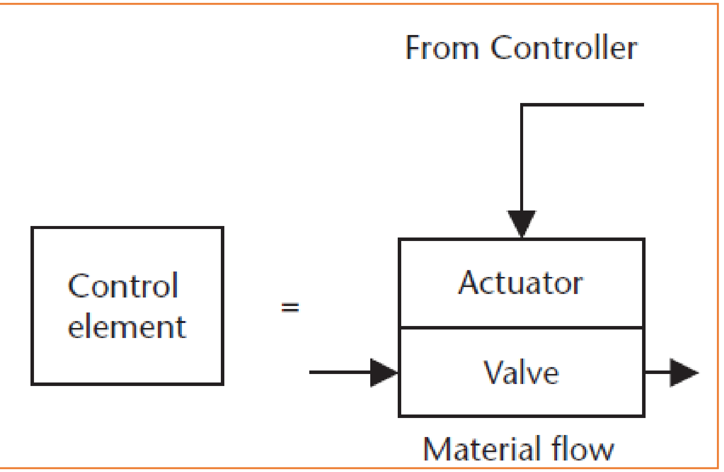


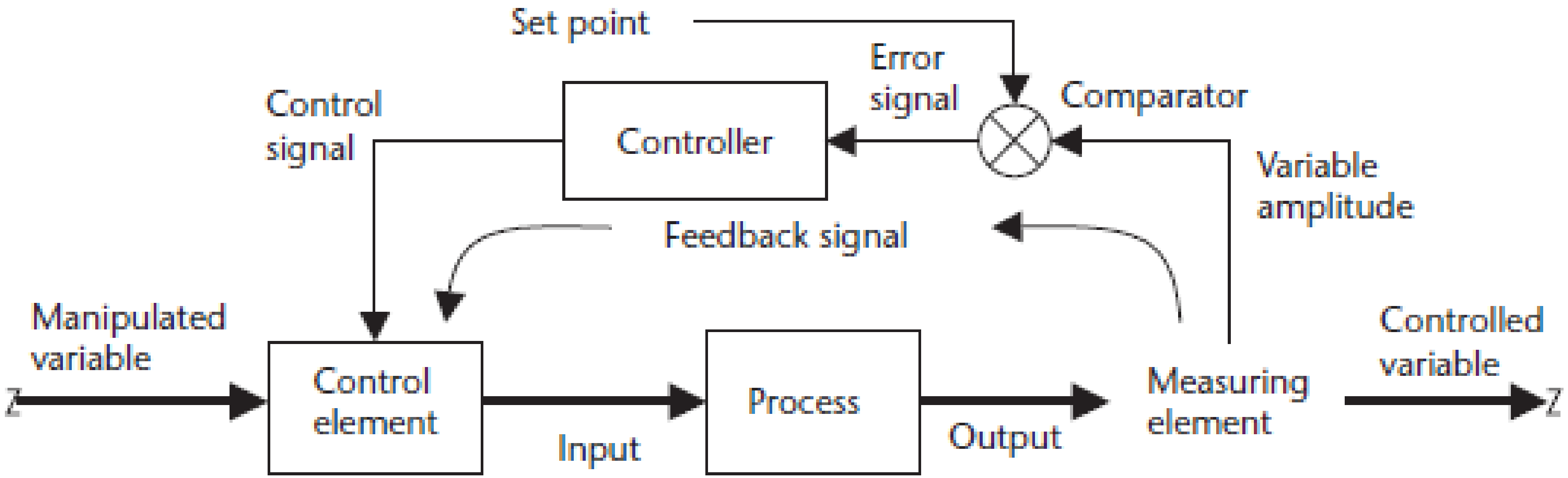
A sensor converts a physical parameter into a form **that can be used or understood -** converting temperature, pressure, force, or flow into an electrical signal, measurable motion, or a gauge reading.

Controller is a microprocessor-based system that determines the next step to be taken in a sequential process or evaluate the error signal in continuous control to determine what action is to be taken.

The controller can condition the signal, such as correcting the signal for temperature effects or nonlinearity in the sensor.







Control Element is the device that controls the incoming material to the process (e.g., the valve). The element is typically a flow control element and can have an On/Off characteristic or can provide liner control.

The control element is used to adjust the input to the process, bringing the output variable to the value of the set point.

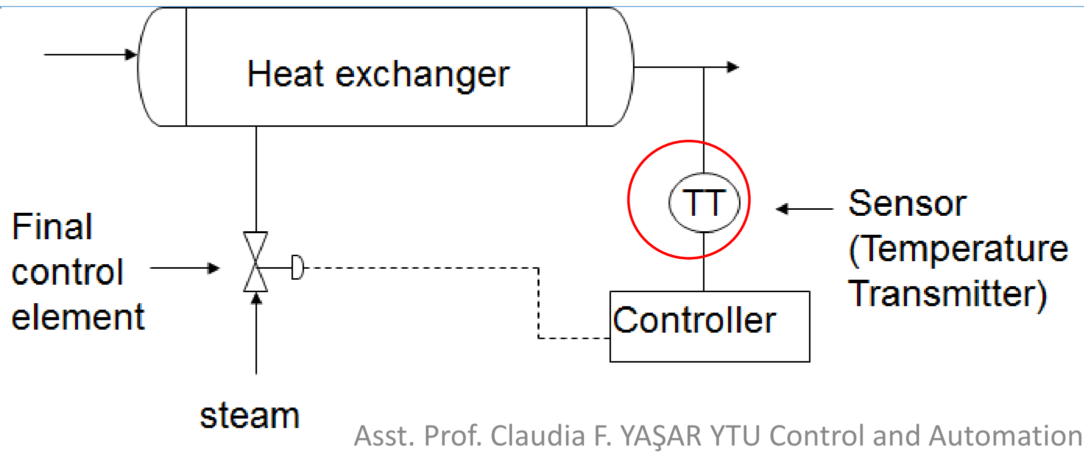
How is Process Control Documented?

In standard Drawing:

- ❑ process equipment is drawn in solid lines
- ❑ sensors are designated by a circle connected to the point in the process where they are located
- ❑ process control loops are shown by dashed lines. _ _ _ _ _ .

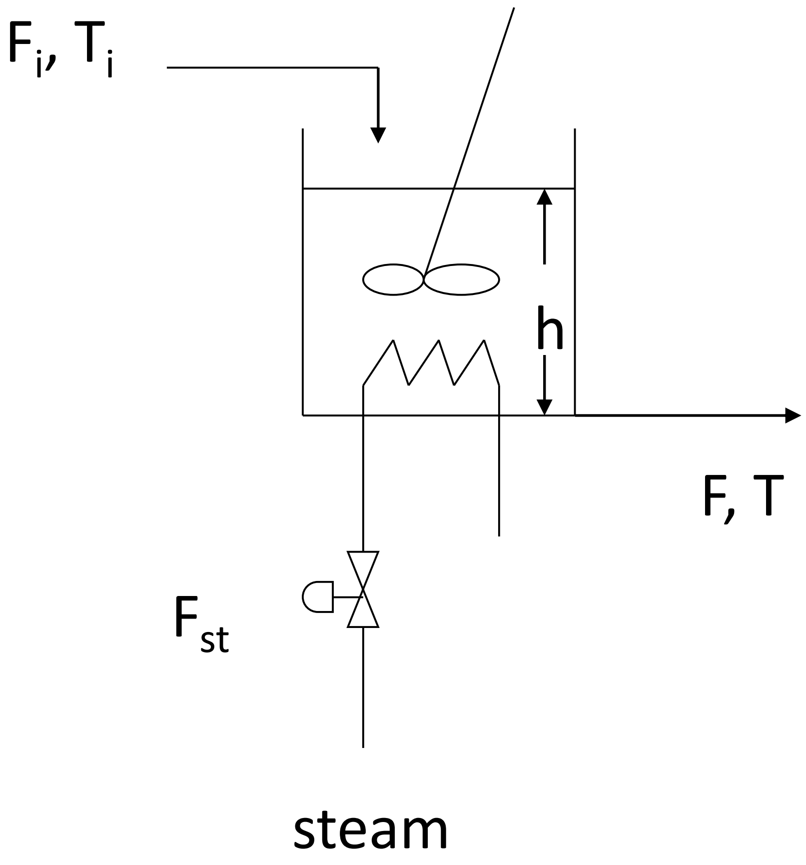
- The first letter in the instrumentation symbol indicates the type of variable measured.
- The subsequent letter(s) give information about the function performed.

A	analyzer
F	Flow rate
L	Level of liquid or solid
P	Pressure
T	temperature



❑ In order to avoid misunderstanding , standard symbols developed by Instrument Society of America (ISA) are used.

Thank heating system



A liquid enters to the tank with a flow rate F_i (ft^3/min) and a temperature of T_i (^0F), where it is heated with steam having a flow rate of Fst (lb/min). Let F and T be the flow rate and temperature of the stream leaving the tank.

The tank is considered to be **well stirred**, (the temperature of the effluent is equal to the temperature of the liquid in the tank).

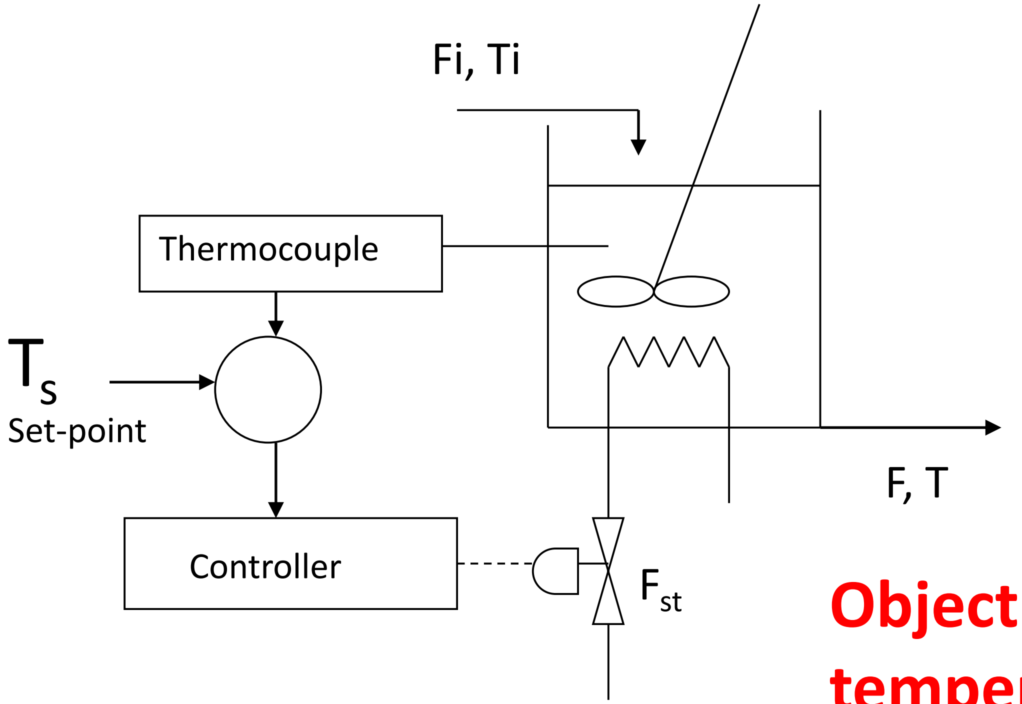
The control objectives of the heater are:

1. To keep the **effluent temperature T** at the desired value T_s.
2. To **keep the volume of the liquid** in the tank at a desired value V_s.

Disturbed by external factors such as changes in the feed flow rate F_i and temperature T_i.

Feedback control

A thermocouple measures the temperature of the fluid in the tank. Then this temperature is compared with the desired value yielding a deviation $\varepsilon = T_s - T$

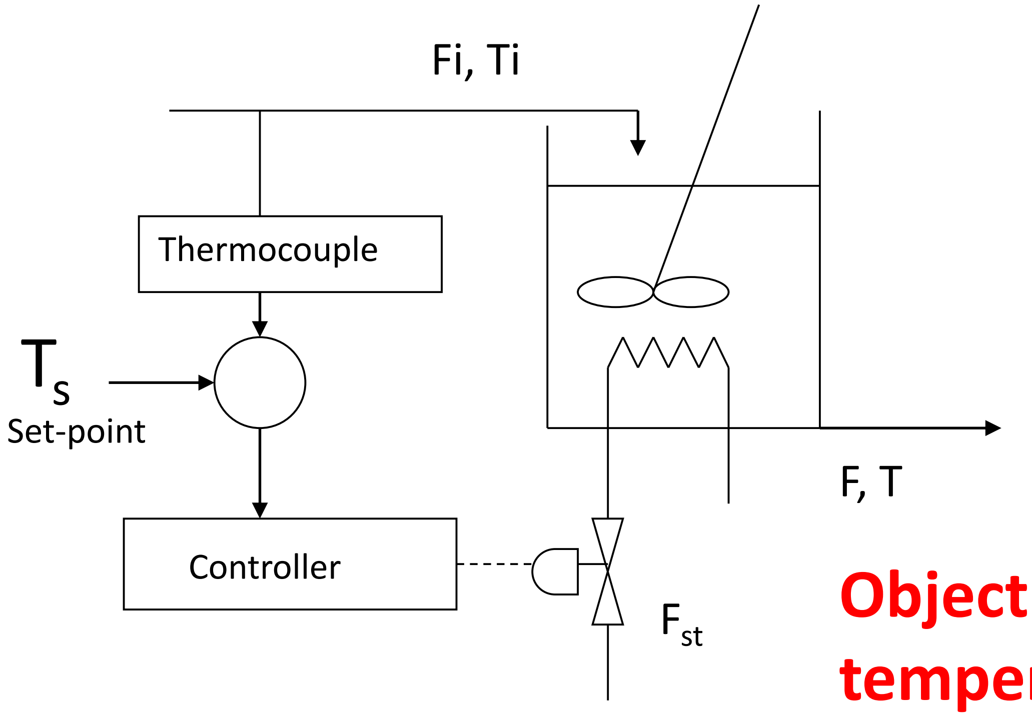


The value of deviation ε is sent to a control mechanism which decides what must be done to turn back to the desired value T_s.

Objective: to keep the effluent temperature T at the desired value T_s.

Feedforward control

This controller does not wait until the effects of the disturbances has been felt by the system, but acts appropriately before the external disturbance affects the system anticipating what its effect will be.

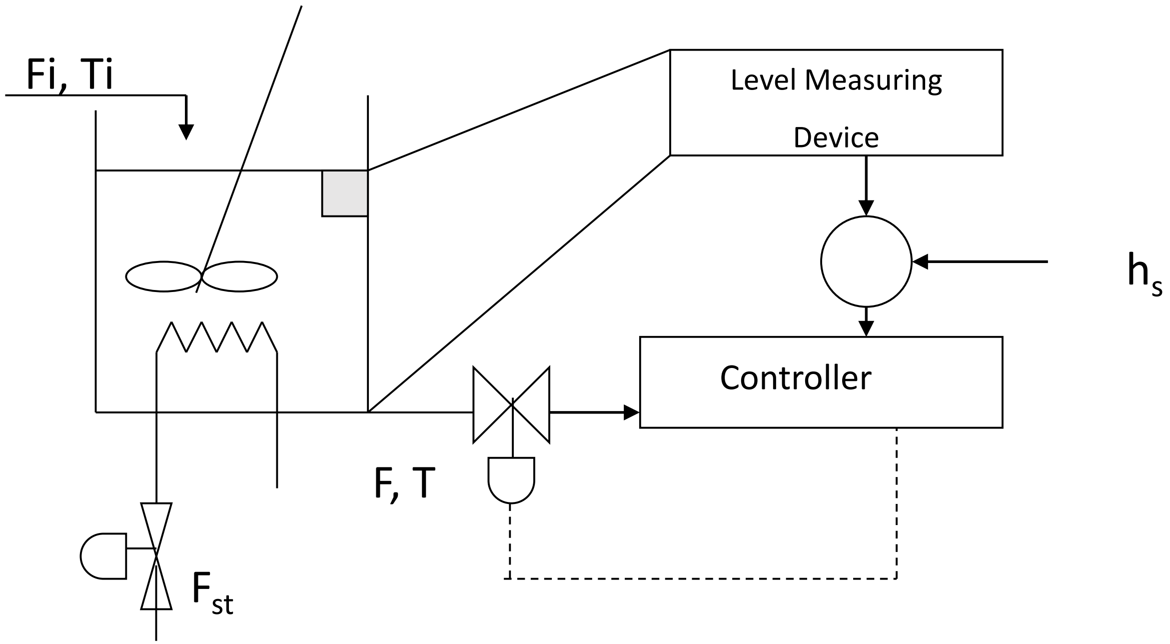


Objective: to keep the effluent temperature T at the desired value Ts.

Objective: to keep the volume of the liquid in the tank at a desired value V_s.

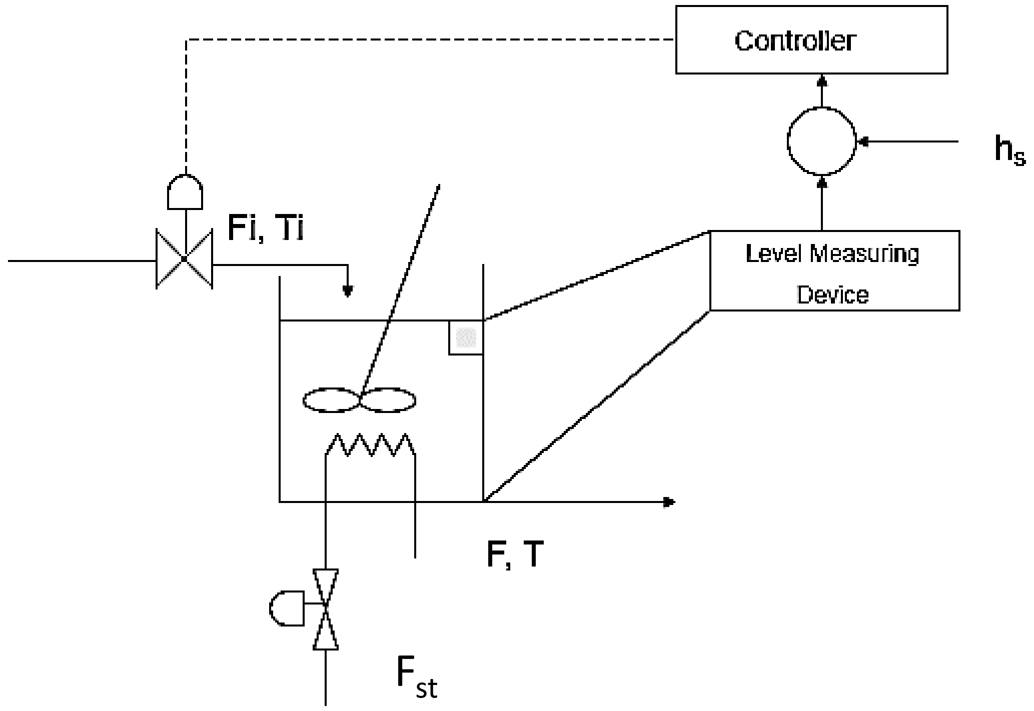
Keep the volume at its set point or keep the liquid level $h_{s.}$

We measure the level of the liquid in the tank and we open or close the effluent flow rate.



Feedback control

Objective: to keep the volume of the liquid in the tank at a desired value V_s.



Input variables are: F_i, T_i and F_{st} (which denote the effect of surroundings on the process)
Output variables are: F, V and T (which denote the effect of process on the surroundings)

Feedback control

The input variables can be further classified as:

1. Manipulated (or adjustable) variables, if their values can be adjusted freely by the human operator or a control mechanism.
2. Disturbances, if their values are not the result of adjustment by an operator or a control system.

The output variables are also classified as:

1. Measured output variables, if their values are known by directly measuring them.
2. Unmeasured output variables, if they are not or cannot be measured directly.

Note:

- Understand your process, as well as your control objectives

  What needs to be controlled? Which variables effect each other (and how)? Where does variability hurt you most? Etc.

- Remember there's a dynamic component.

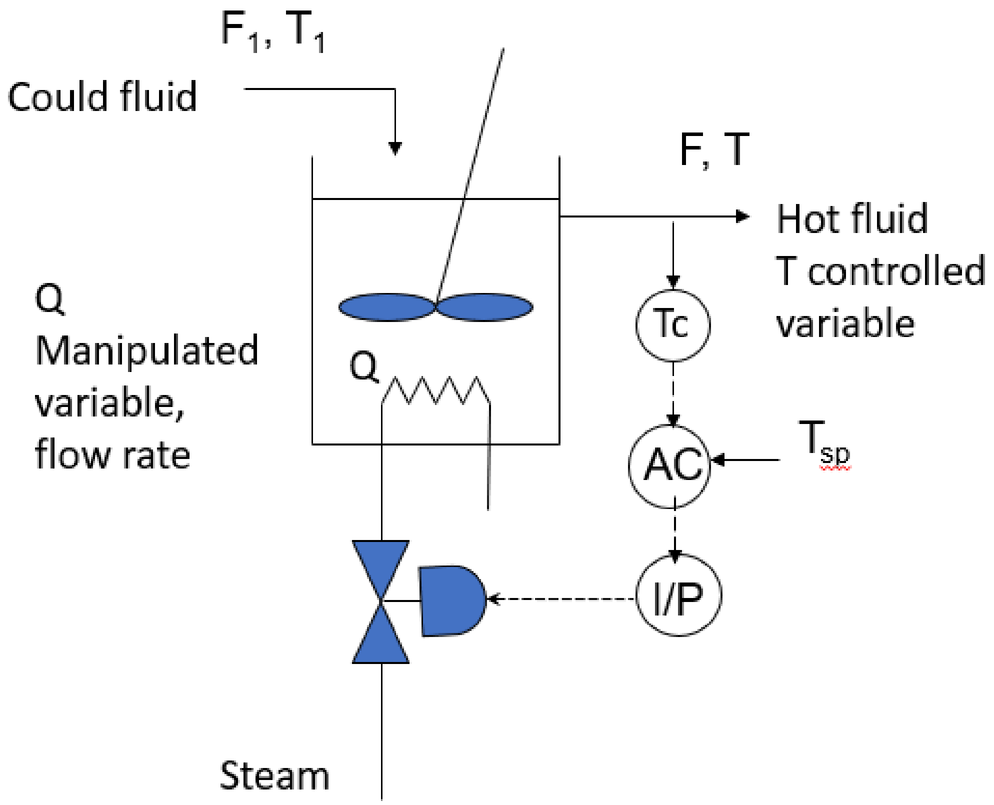
- Think about control early in design phase.

MODEL-BASED DESİGN THERMAL PROCESS CONTROL

Transfer functions

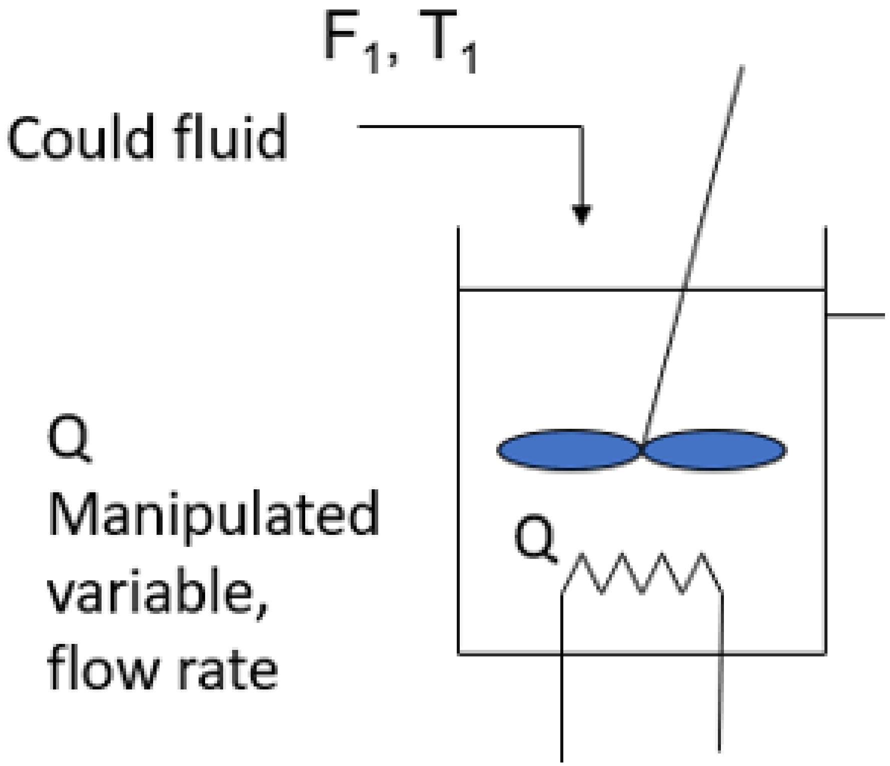
Example: **Heating process: modelling, control and Instrumentation**

Consider a Stirred-Tank heating process with constant Holdup and the following assumptions: perfect mixing, thus, the exit temperature *T* is also the temperature of the tank contents; the density ρ and heat capacity *Cp* of the liquid are assumed to be constant, thus, their temperature dependence is neglected; heat losses are negligible.



$F_1 = 2x10^{-5}\ \frac{m^3}{min}$
$\rho = 10^6\ \frac{g}{m^3}$
$C_p = 1\ \frac{K\ cal}{g\ °C}$
$V = 1\ \mathrm{m}^3$
$T_1 = 30\ \ °C$
$Q = 1200\ \frac{K\ cal}{min}$

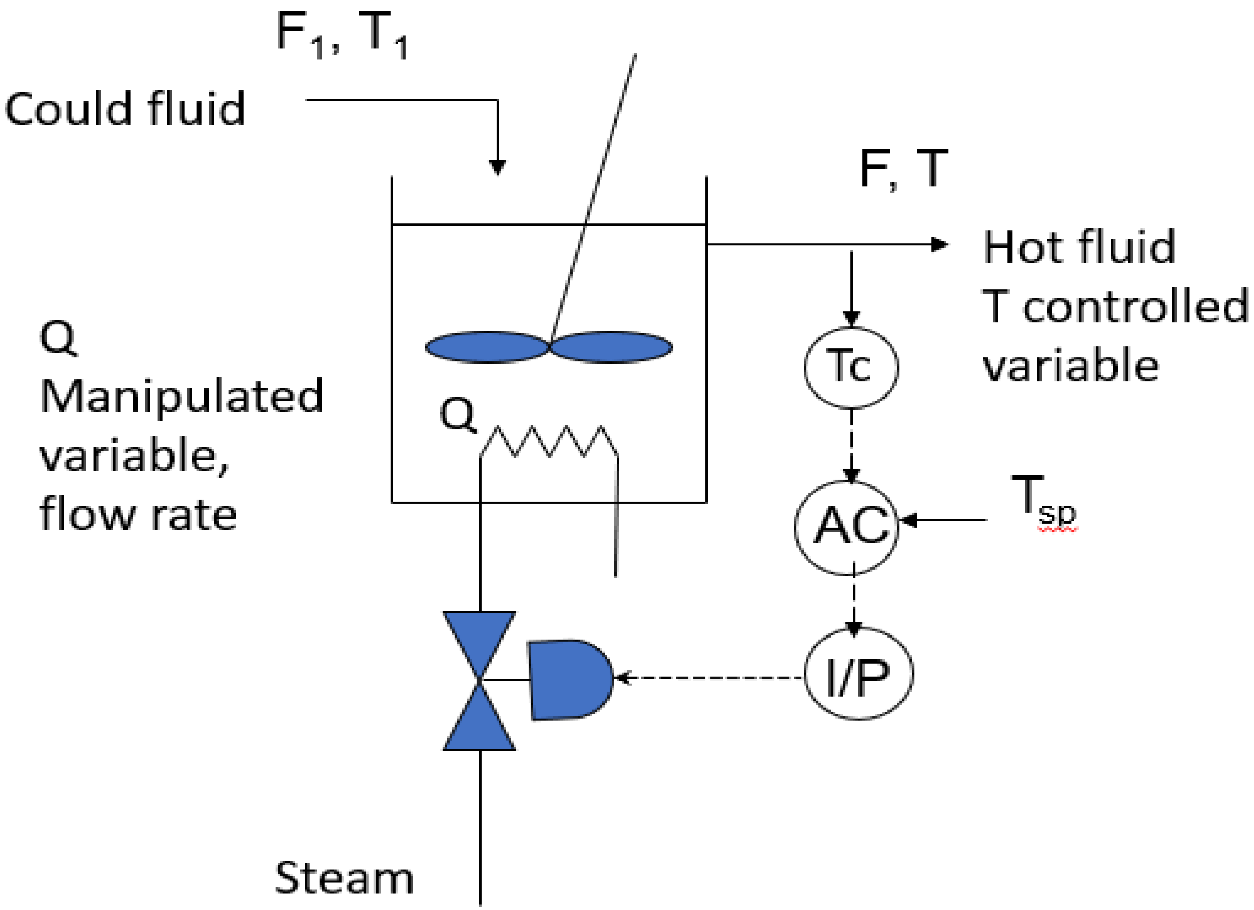
- Determine the total and energy balance to obtain dT/dt.
- Use the given parameters and calculate the nominal steady-state temperature, T.



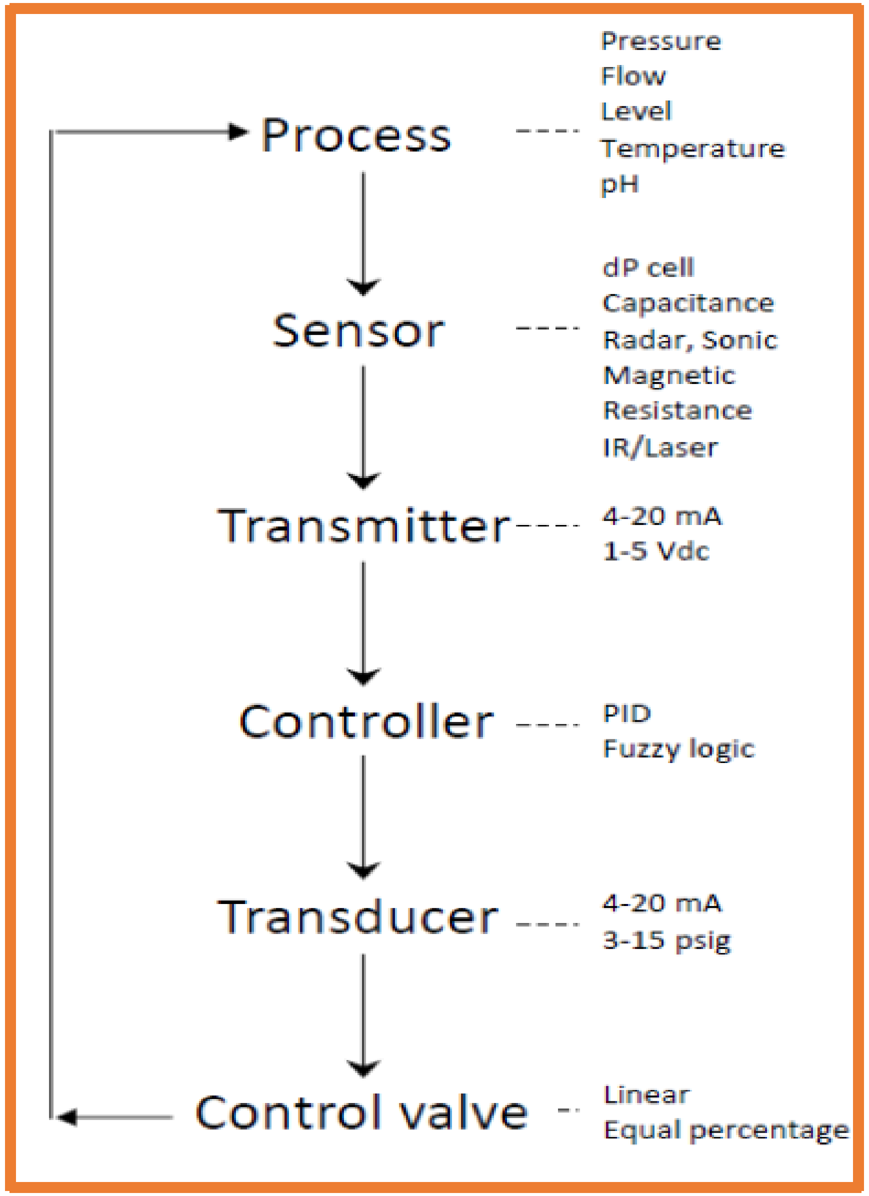
$F_1 = 2x10^{-5} \quad \frac{m^3}{min}$
$\rho = 10^6 \quad \frac{g}{m^3}$
$C_p = 1 \quad \frac{K\ cal}{g\ ℃}$
$V = 1\ \mathrm{m}^3$
$T_1 = 30 \quad ℃$
$Q = 1200 \quad \frac{K\ cal}{min}$

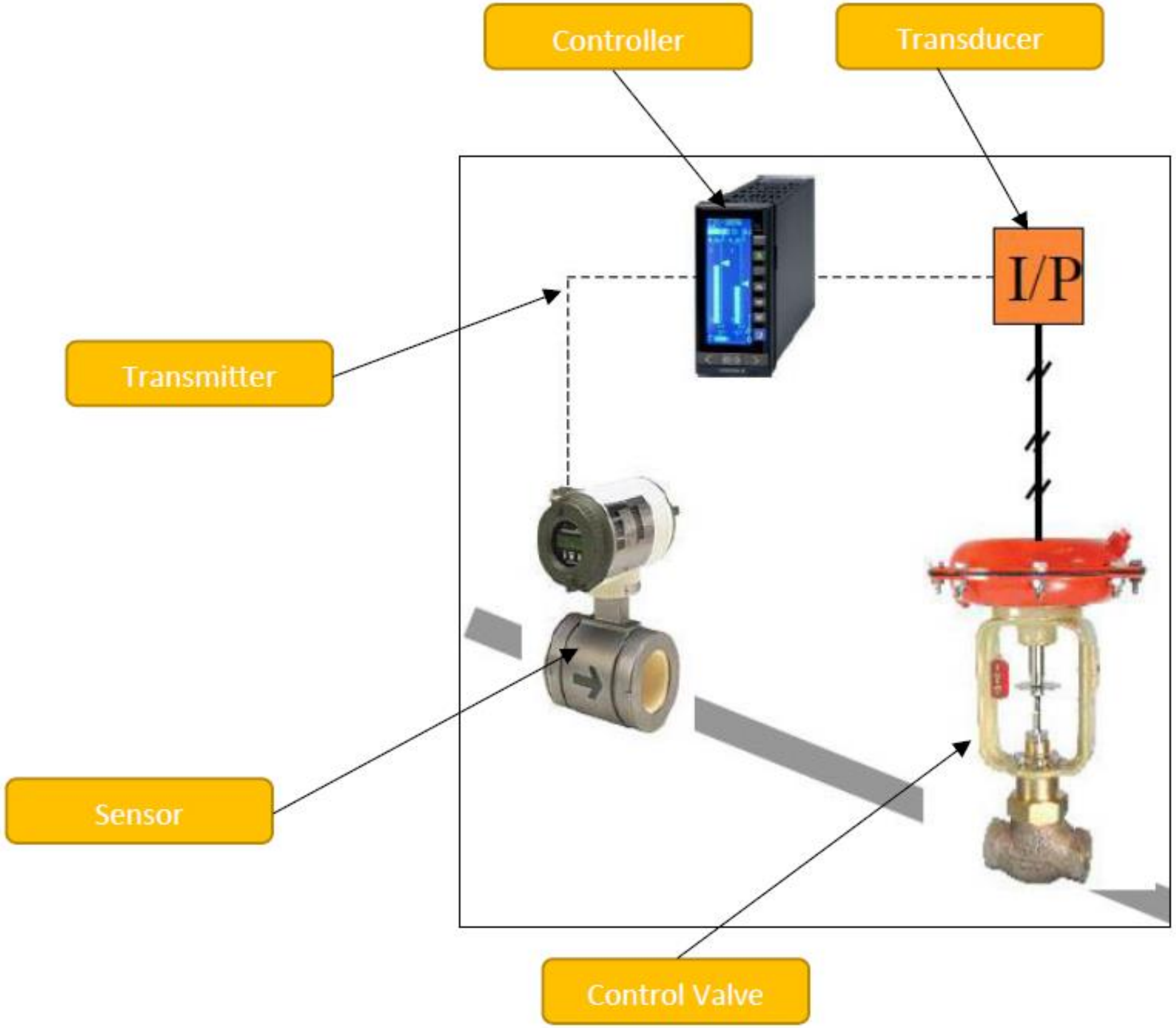
•Propose a block diagram to control the liquid temperature T=Tsp. The controller consist of a single feedback control loop to keep an T_{sp} output temperature. Include all the required instrumentation blocks, transfer functions, and choose a regulator.

•Describe each of the transfer functions, and calculate transfer function parameters, when possible, by using the given values.



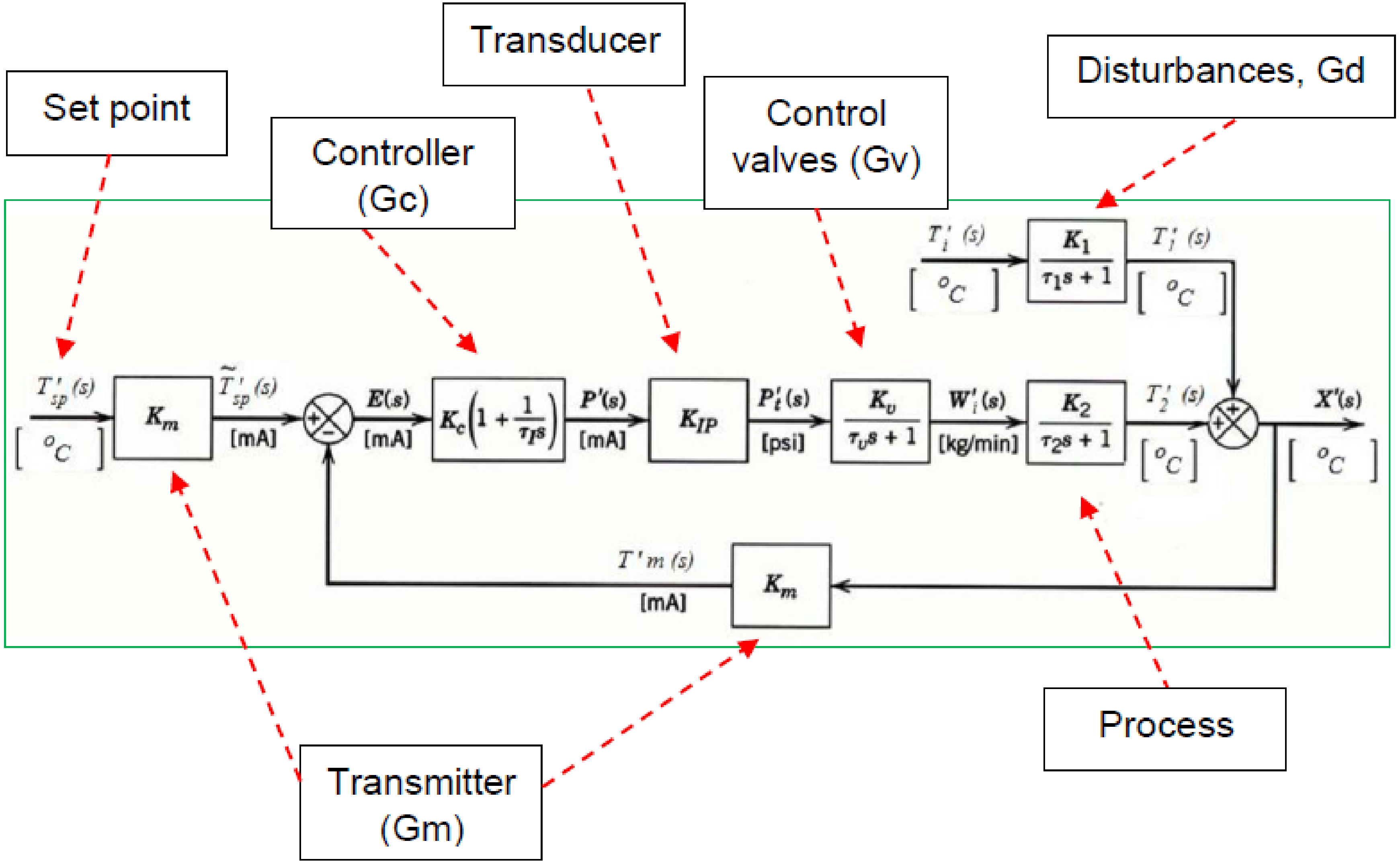
Process Control Loop





Thermal Process Control

➢ **Overall**

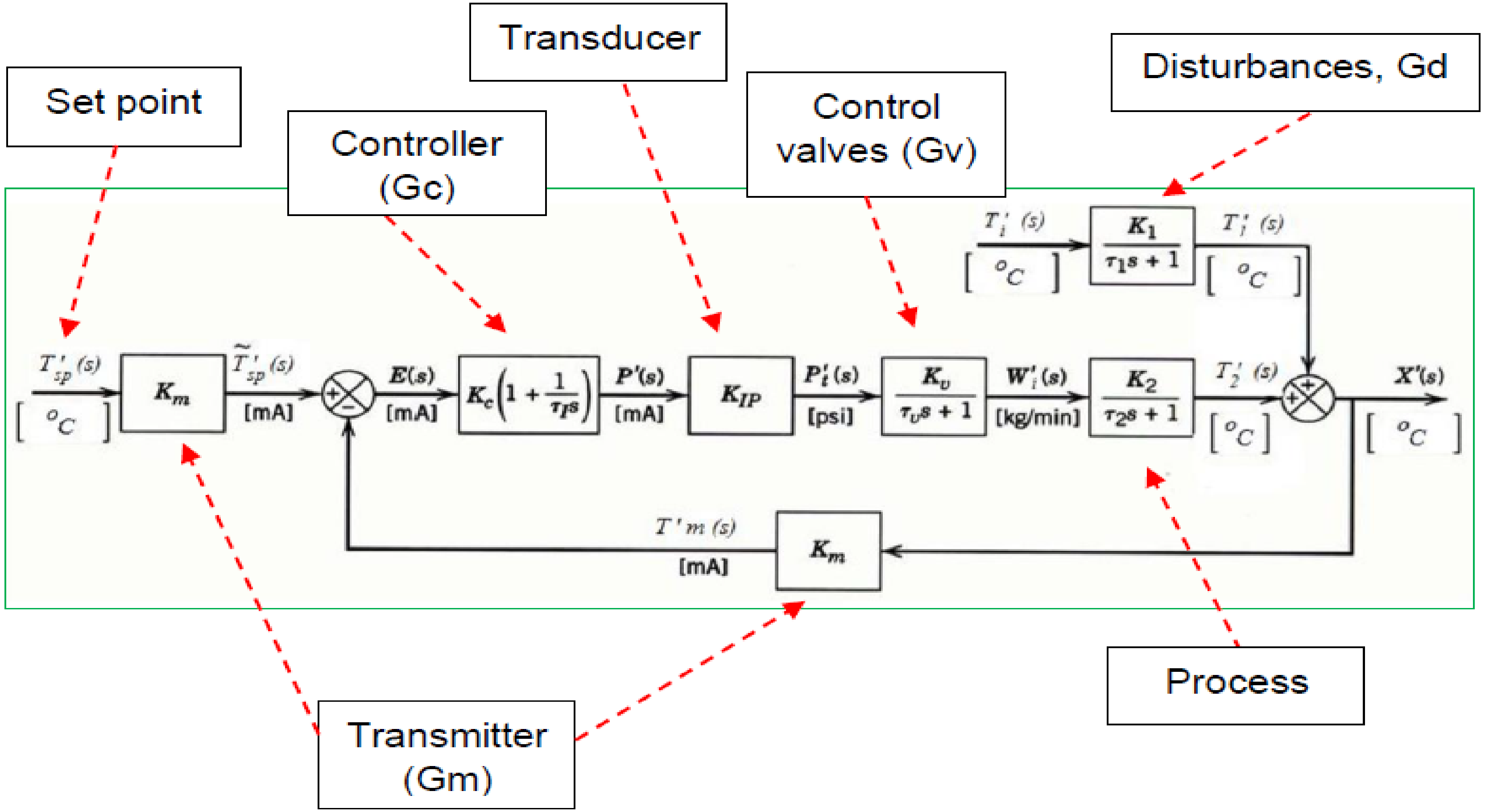


Components of a Control Loop

Control Objective = Set Point (T_{SP})

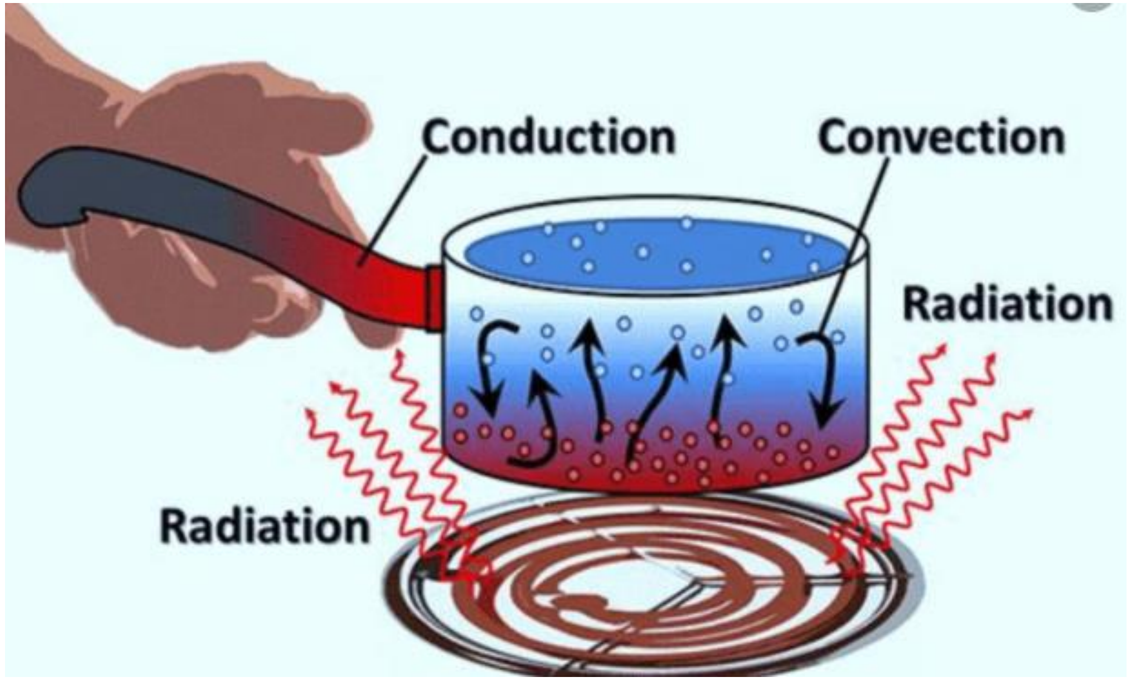
- System Output X'(s)
- Measured Process Variable X'(s)
- Controlled Variable X'(s)
- System reference $T'_{sp}(s)$
- PID: Controller Output P'(s)
- Manipulated Variable $W_i'(s)$
- Disturbances $T_i'(s)$

➢ **Overall**

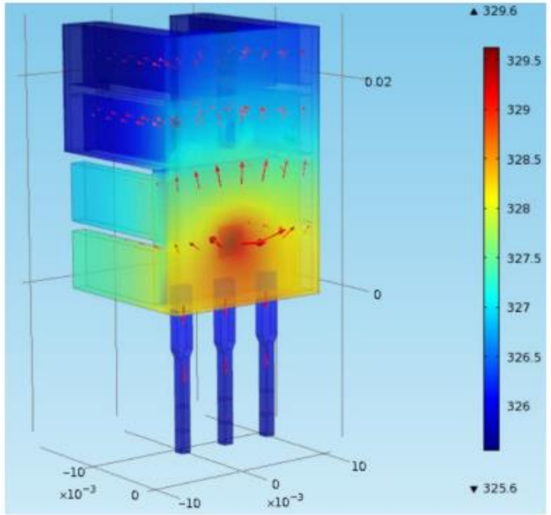


Heat energy transfer

Heat energy is transferred from one point to another using any of three basic methods: conduction, convection, and radiation. These modes of transfer can be considered separately, but in practice two or more of them can be present simultaneously.

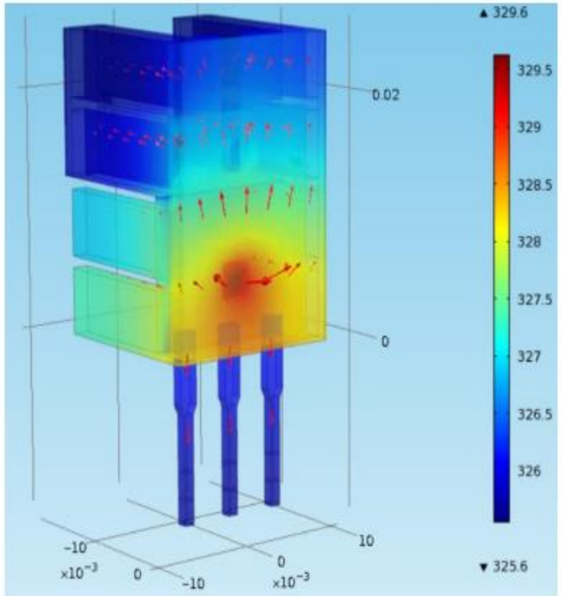


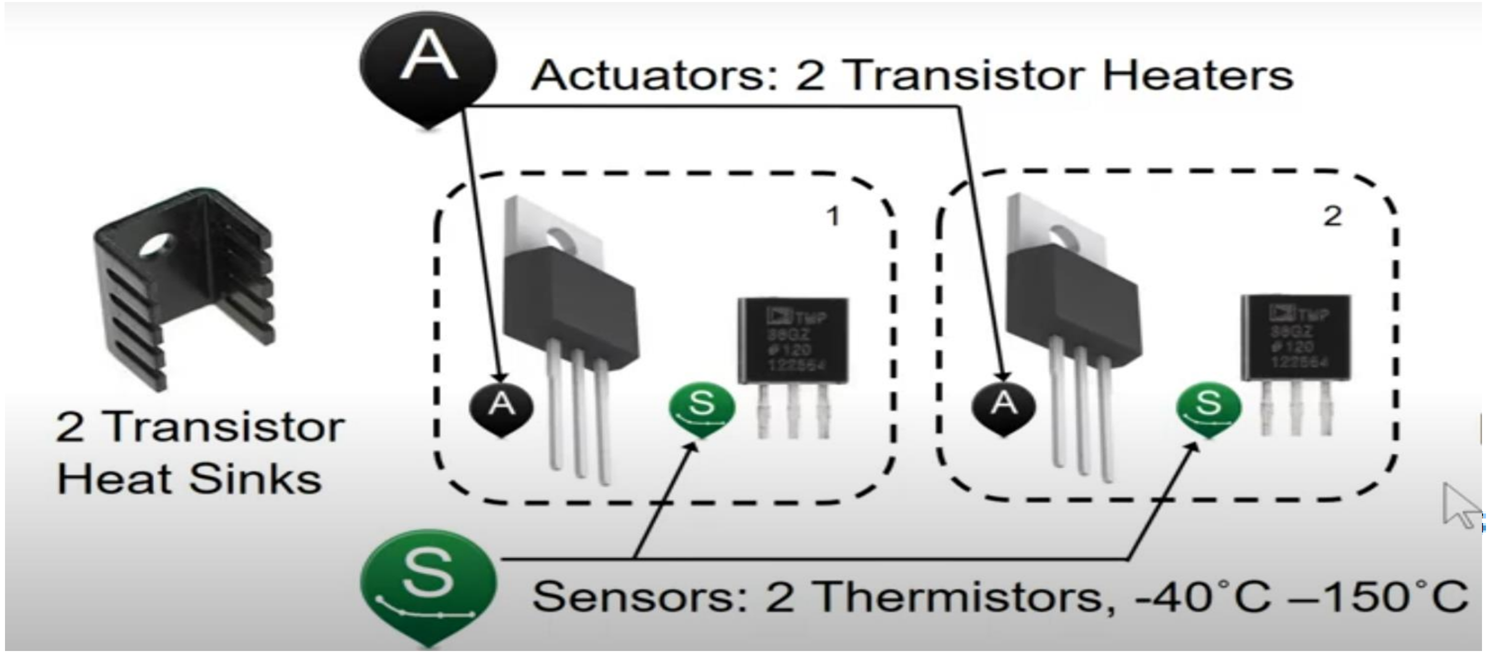
Temperature Modeling



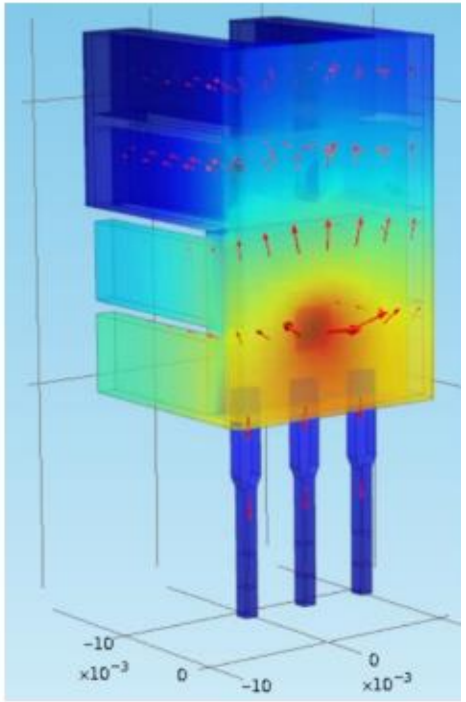
Use the energy balance to create a dynamic model of the dynamic response between input power to the transistor and the temperature sensed by a thermistor. The full energy balance includes convection and radiation terms.

https://apmonitor.com/pdc/index.php/Main/ArduinoModeling





The heat generated by the transistor transfers away from the device primarily by convection but radiative heat transfer may also be a contributing factor. The radiative heat transfer can be included in the model to determine what fraction of heat is lost by convection and heat radiation. Heat transfer is improved with a thermal coupling (white epoxy) that connects the two components.



Quantity
Initial temperature (T_0)
Ambient temperature (T_∞)
Heater output (Q)
Heater factor (α)
Heat capacity (C_p)
Surface Area (A)
Mass (m)
Overall Heat Transfer Coefficient (U)
Emissivity (ε)
Stefan Boltzmann Constant (σ)

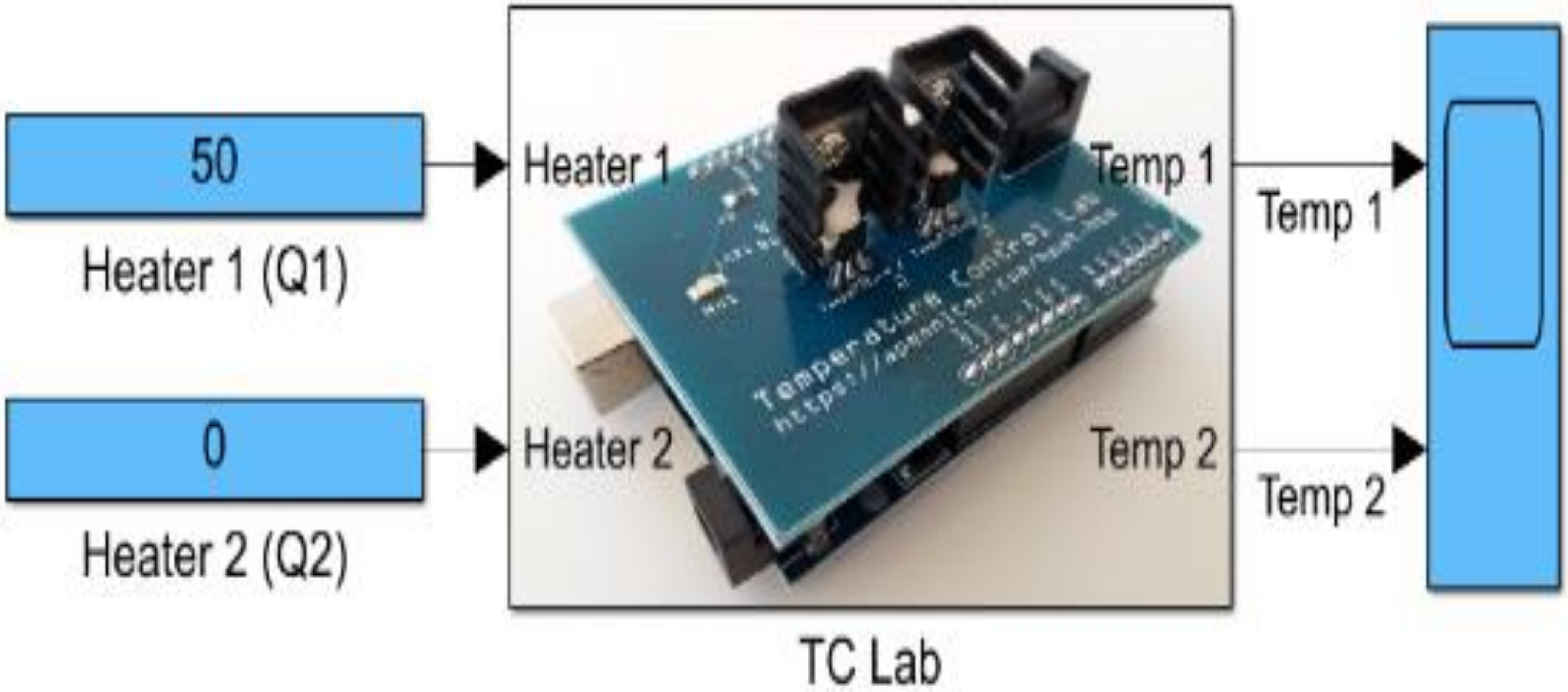
$$m\,c_p\frac{dT}{dt} = \sum \dot{h}_{in} - \sum \dot{h}_{out} + Q$$

Q is the rate of heat transfer

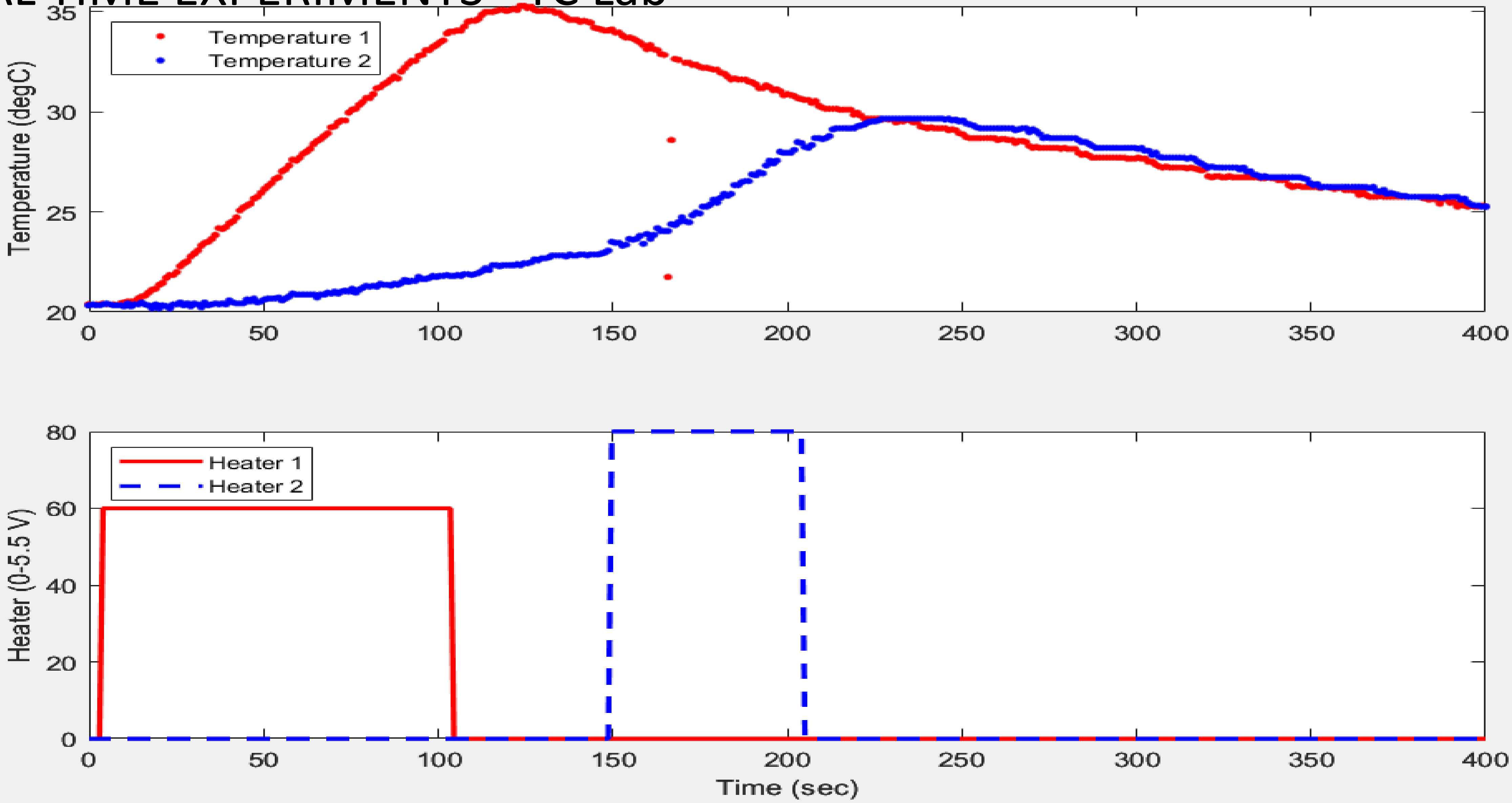
$$m\,c_p\frac{dT}{dt} = U\,A\,(T_\infty - T) + \epsilon\,\sigma\,A\,\left(T_\infty^4 - T^4\right) + \alpha Q$$

Convection **Radiation** **Heater**

REAL TIME EXPERİMENTS - TC Lab -

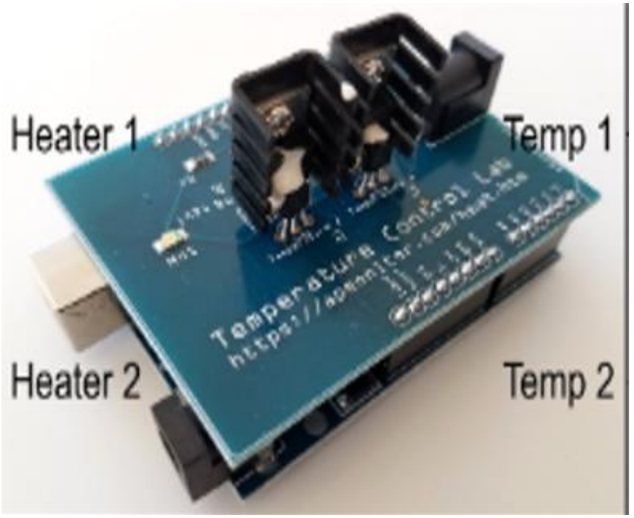


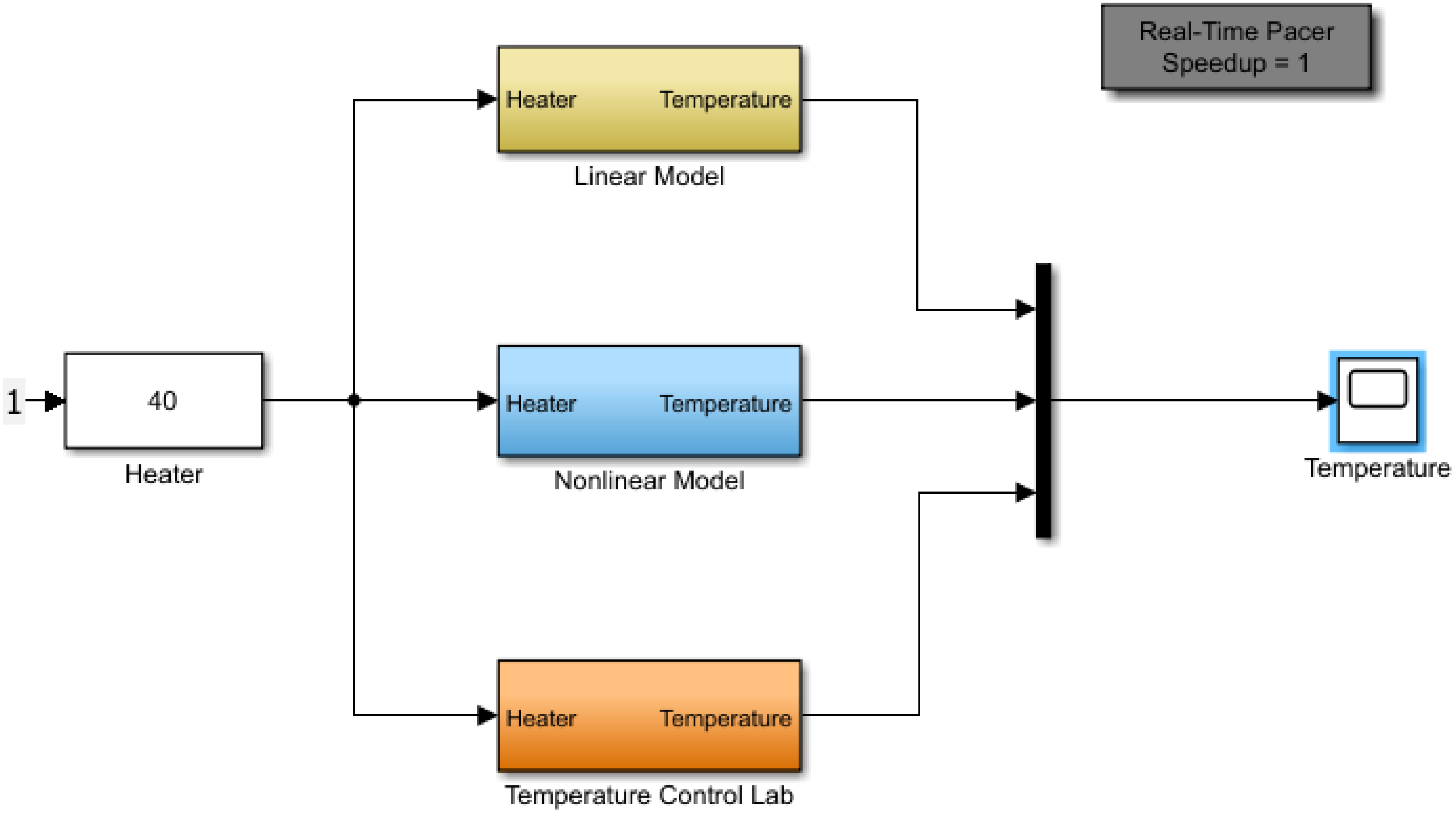
REAL TIME EXPERİMENTS - TC Lab -



REAL TIME EXPERİMENTS - TC Lab -

m = 0.001; % kg (1 gm)
% heat transfer coefficient
U = 200; % W/m^2-K
% surface area
A = 2 / 100^2; % m^2
% heat capacity
Cp = 4900.0; % J/kg-K





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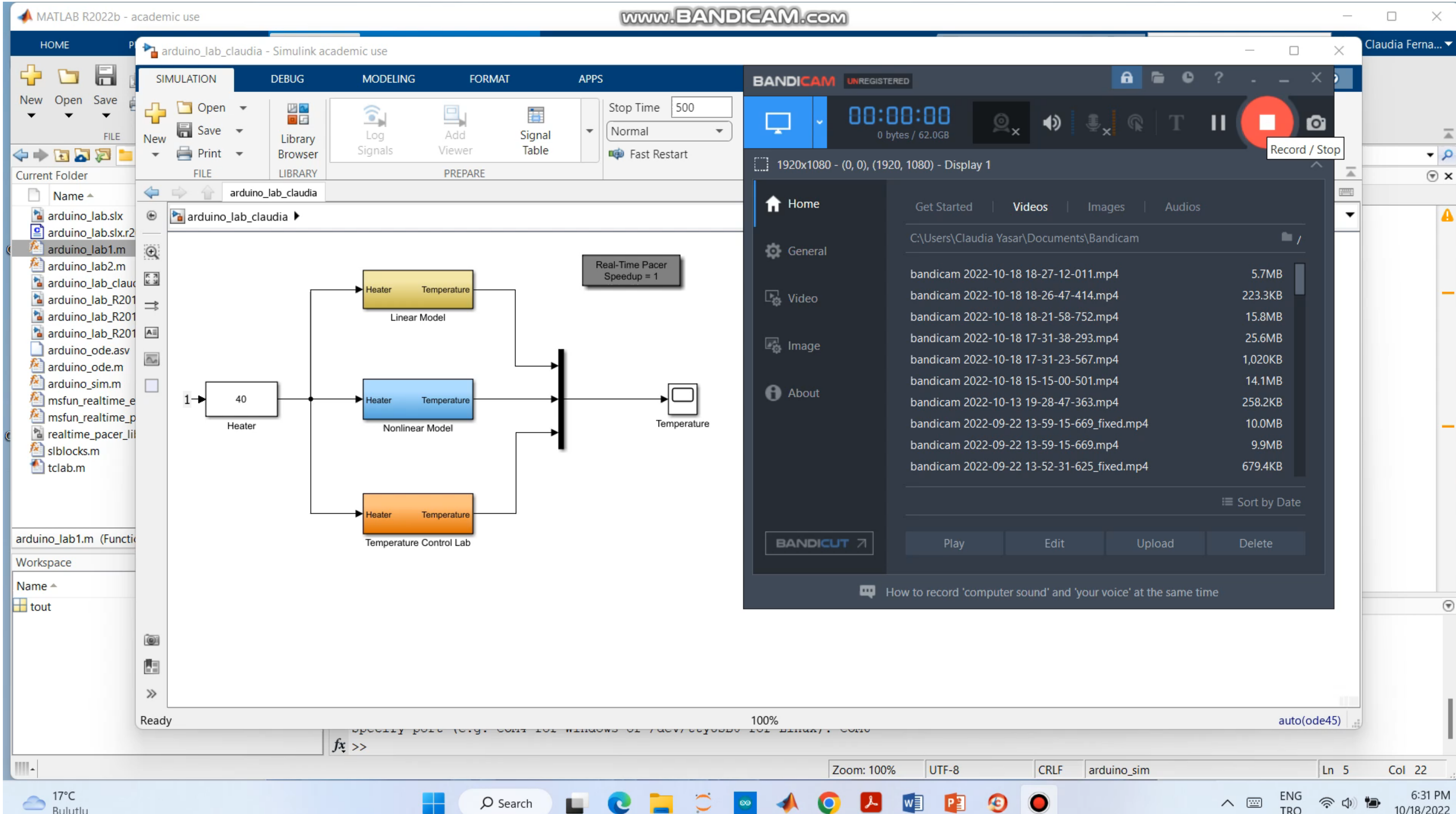

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Graphical Method: FOPDT to Step Test

A first-order linear system with time delay is a common empirical description of many stable dynamic processes. The equation

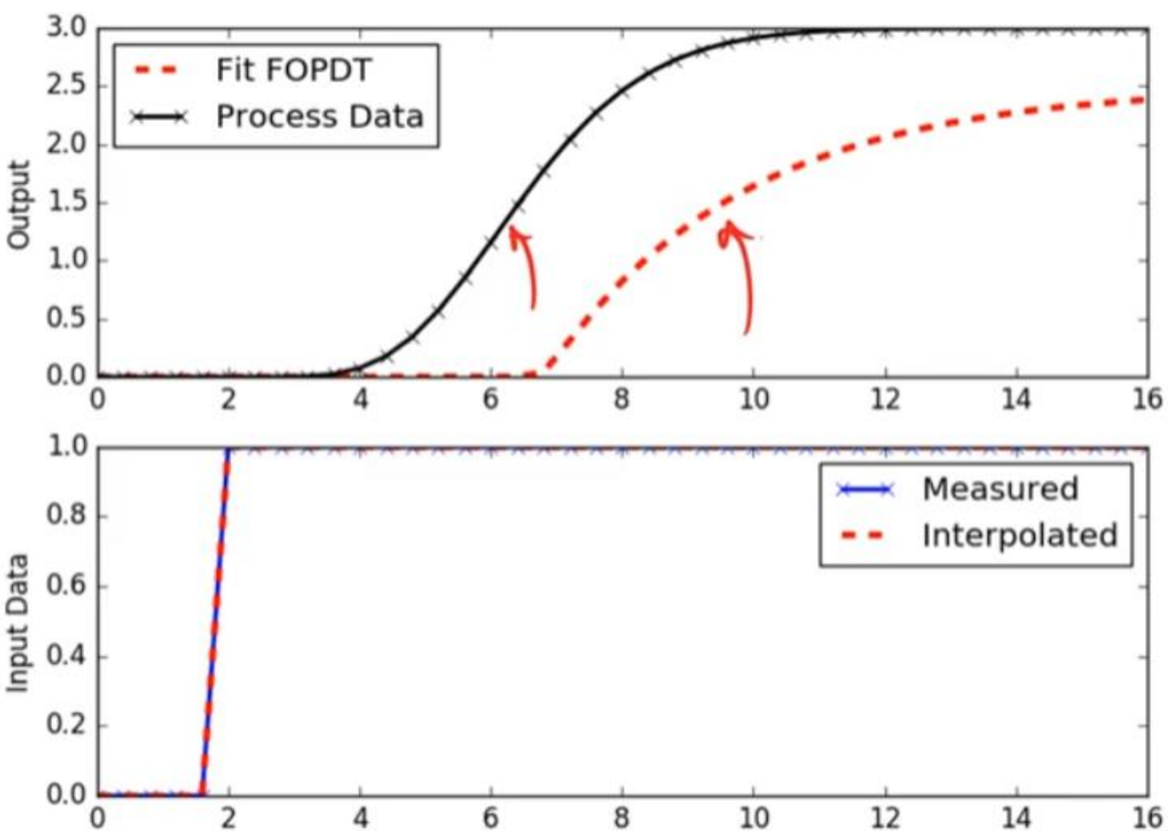
$$\tau_p \frac{dy(t)}{dt} = -y(t) + K_p u\left(t - \theta_p\right)$$

has variables $y(t)$ and $u(t)$ and three unknown parameters.

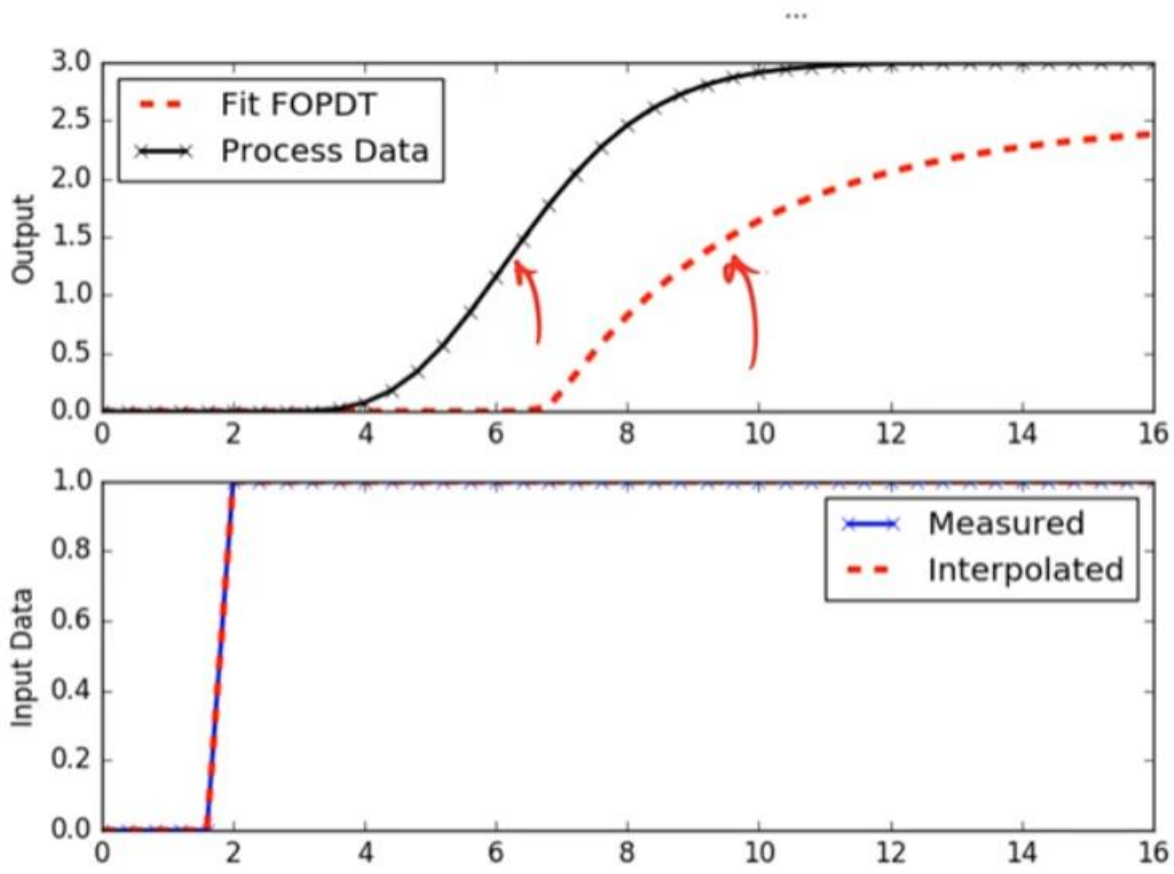
$$K_p \quad = \text{Process gain}$$

$$\tau_p \quad = \text{Process time constant}$$

$$\theta_p \quad = \text{Process dead time}$$



Graphical Method: FOPDT to Step Test



Step test data are convenient for identifying an FOPDT model through a graphical fitting method. Follow the following steps when fitting the parameters K_p, τ_p, θ_p to a step response.

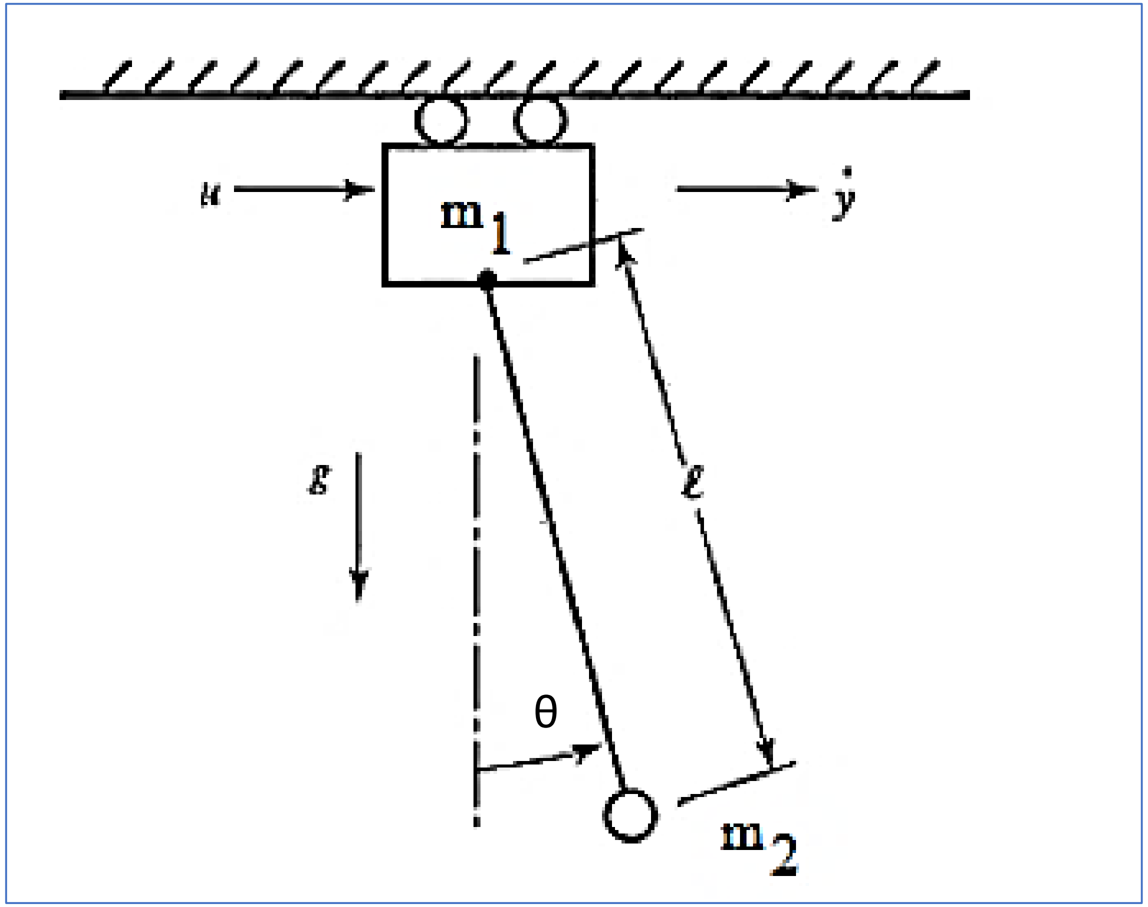
1. Find Δy from step response
2. Find Δu from step response
3. Calculate $K_p = \dfrac{\Delta y}{\Delta u}$
4. Find θ_p, apparent dead time, from step response
5. Find $0.632\Delta y$ from step response
6. Find $t_{0.632}$ for $y(t_{0.632}) = 0.632\Delta y$ from step response
7. Calculate $\tau_p = t_{0.632} - \theta_p$. This assumes that the step starts at $t = 0$. If the step happens later, subtract the step time as well.

MODEL-BASED DESIGN

State Space Models

The state space model of a crane system.

Obtain the system dynamic equation and the state space model equation of the pendulum with an adjustable overhead cart shown in the figure.

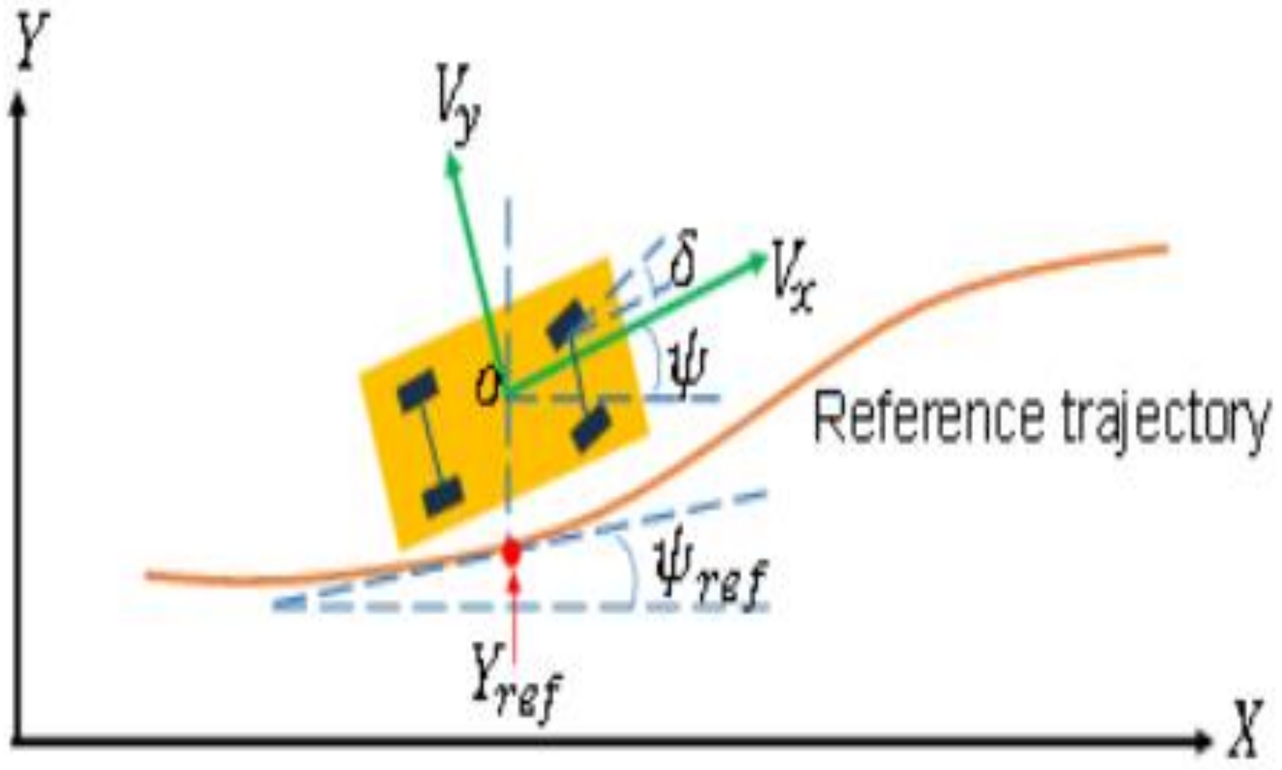


A crane system is can be described by the following dynamic equations:

Lateral Vehicle Dynamics

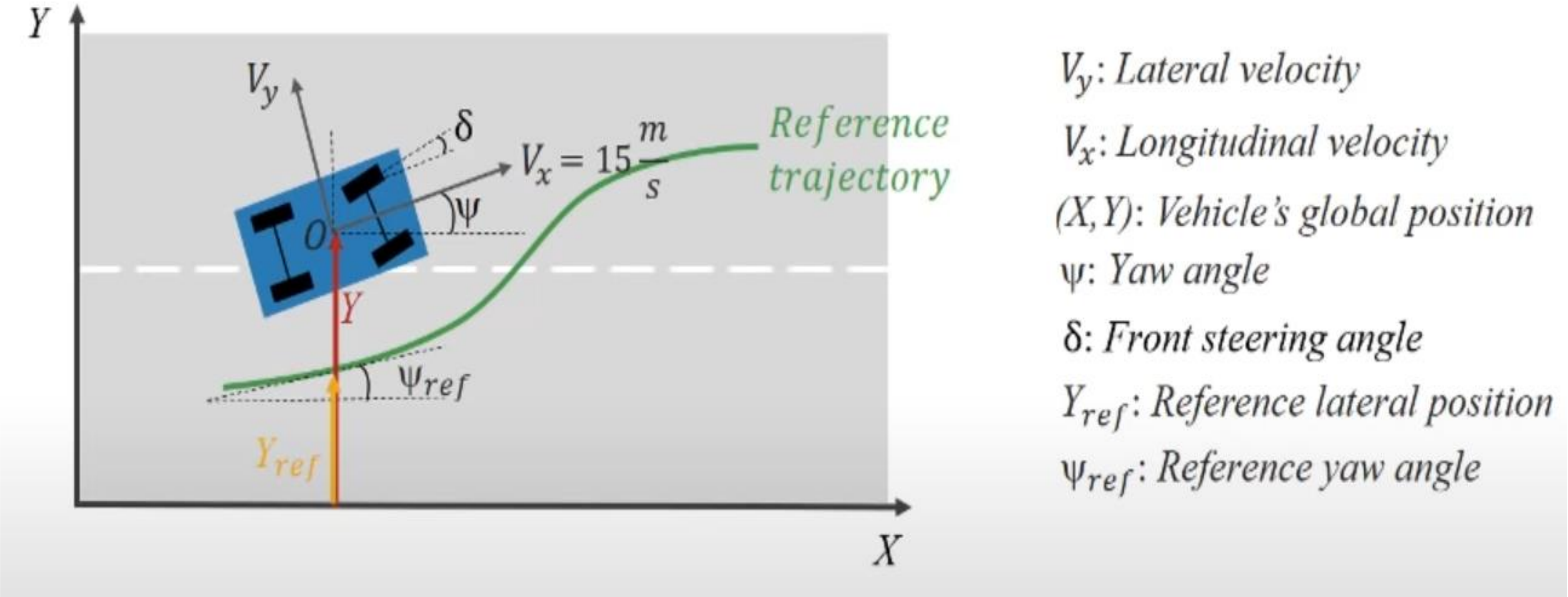
Describe the lateral vehicle dynamics, this example uses a ***bicycle model*** **with two degrees of freedom, lateral position and yaw angle.**

- m is the total vehicle mass (kg)
- Iz is the yaw moment of inertia of the vehicle (mNs^2).
- lf is the longitudinal distance from the center of gravity to the front tires (m).
- lr is the longitudinal distance from center of gravity to the rear tires (m).
- Cf is the cornering stiffness of the front tires (N/rad).
- Cr is the cornering stiffness of the rear tires (N/rad).



Lateral Vehicle Dynamics

The system dynamics will be used to apply a MPC strategy for finding the optimal steering wheel angle to control the car's longitudinal speed. At each time step, the MPC controller makes predictions about the future lateral positions of the car.



https://www.mathworks.com/matlabcentral/fileexchange/68992-designing-an-mpc-controller-with-simulink

https://www.youtube.com/watch?v=8U0xiOkDcmw&list=PLn8PRpmsu08ozoeoXgxPSBKLyd4YEHww8