Chapter 8: Feedback Controllers

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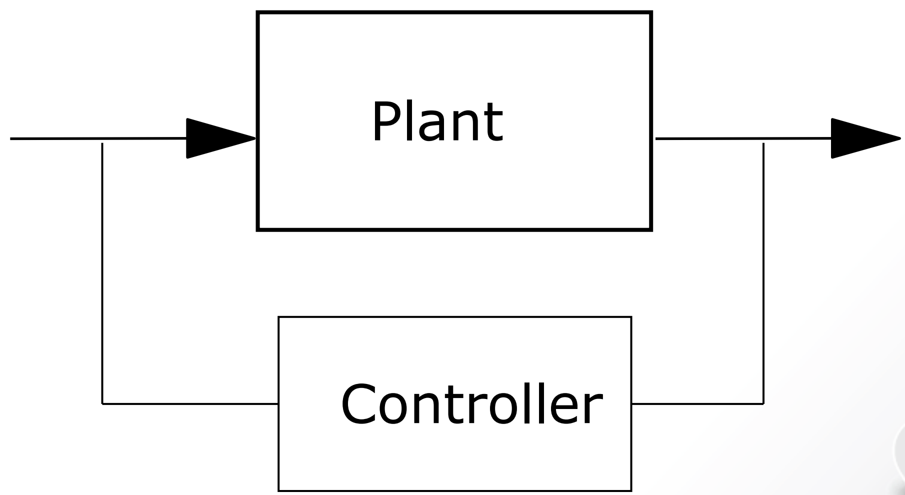
CH3101 - Chapter 8: Feedback Controllers

Feedback Control?



Chapter Overview

This chapter consists of the following topics:

1. Control Algorithms
   - Real Life Feedback Controller
   - Example of Feedback Control
2. Basic Control Modes
   - Proportional Control
   - Integral Control
   - Derivative Control
3. Features of Proportional, Integral and Derivative (PID) Controllers
4. Typical Responses of Feedback Control Systems

Learning Objectives

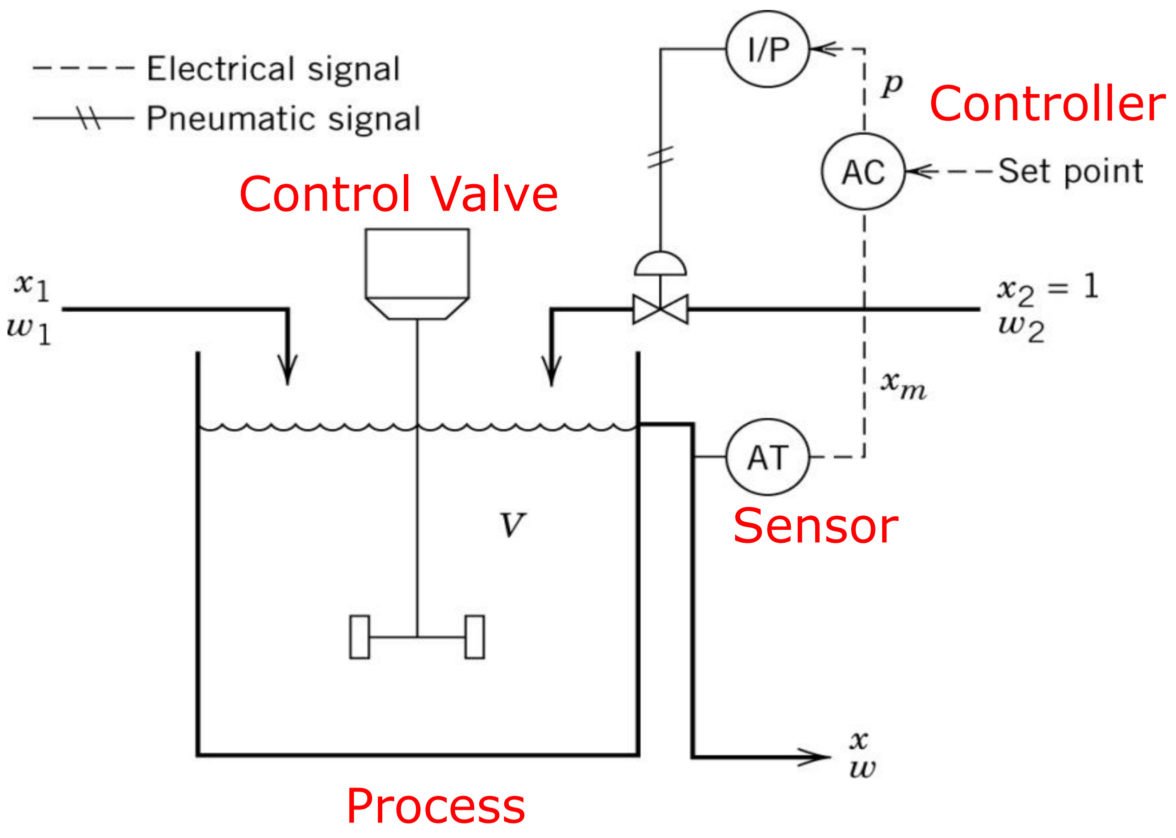
At the end of this chapter, you will be able to:

- Distinguish the different basic control modes
- Describe the features of PID controllers
- Distinguish the three different forms of PID controllers

Recall from Lecture 1

- A controller ensures that the process operates at its design specifications in presence of disturbances.
- The most commonly used control structure is *feedback,* which updates manipulated variables based on measurements of controlled or output variables.
- Unlike feedforward control, feedback control does not anticipate effect of disturbances on controlled variables and is less sensitive to modeling errors (due to direct use of measurements).

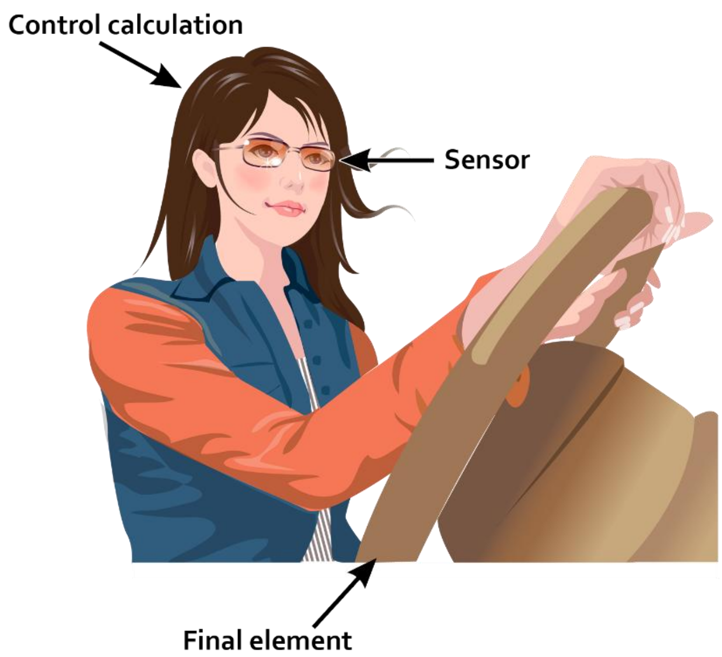
Revisiting the Continuous Blending Tank



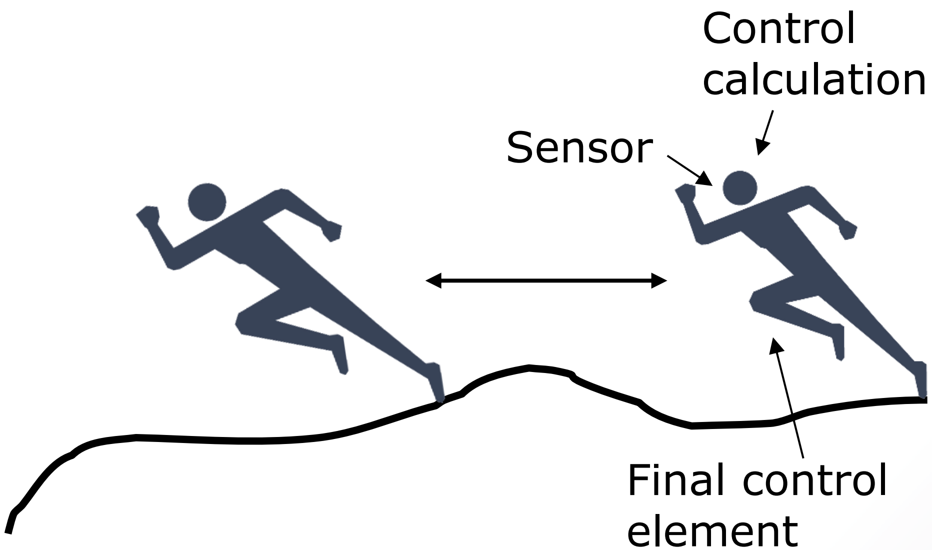
Source: Seborg, D. E., Edgar, T. F., & Mellichamp, D. A. (2011). *Process dynamics and control* (2nd ed.)(pp.186). Hoboken, NJ: Wiley.

Real Life Feedback Controllers

- Feedback control only in industries?

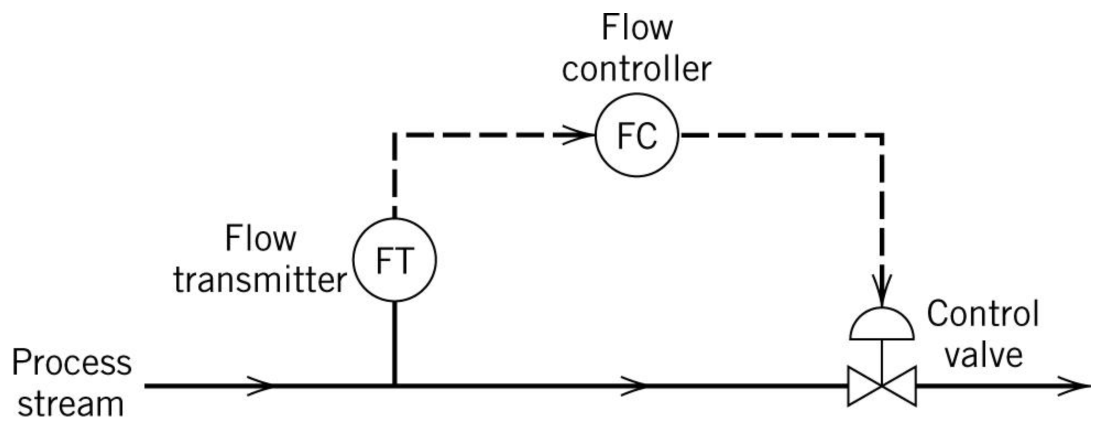


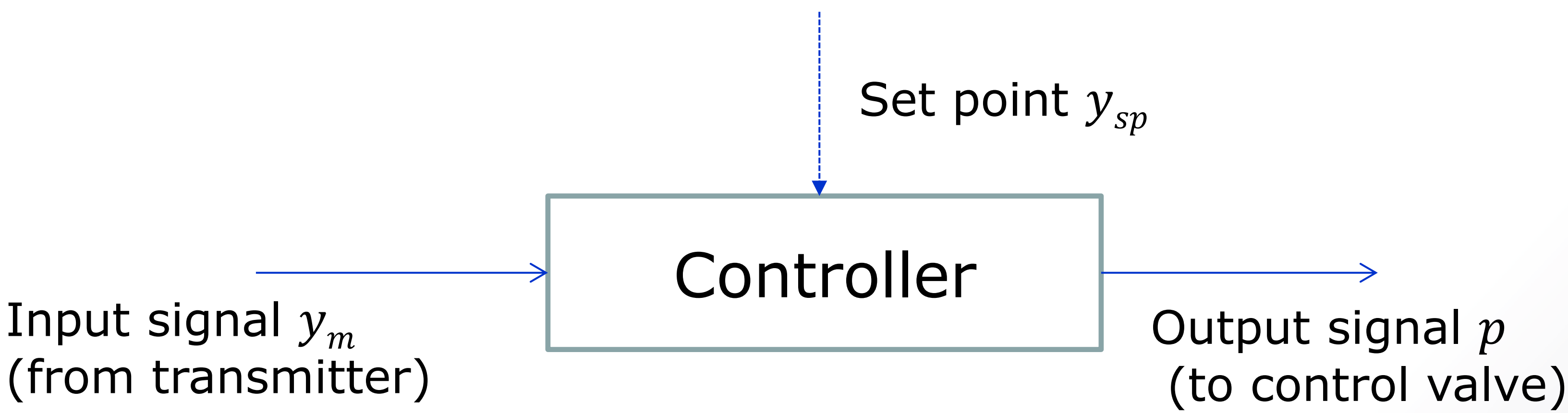
Driving a car



Marathon running

Simple Example of Feedback Control





Source: Seborg, D. E., Edgar, T. F., & Mellichamp, D. A. (2011). *Process dynamics and control* (2nd ed.)(pp.188). Hoboken, NJ: Wiley.

Basic Control Modes

- Proportional/ Integral/ Derivative
- Proportional control (P)
  - Objective is to reduce the error signal to zero
  - Error signal, $e = Y_{sp}(t) - Y_m(t) \qquad (8-1)$
    - Y_{sp} = set point
    - Y_m = measured value of the controlled variable (or equivalent signal from transmitter)

1. Proportional Control

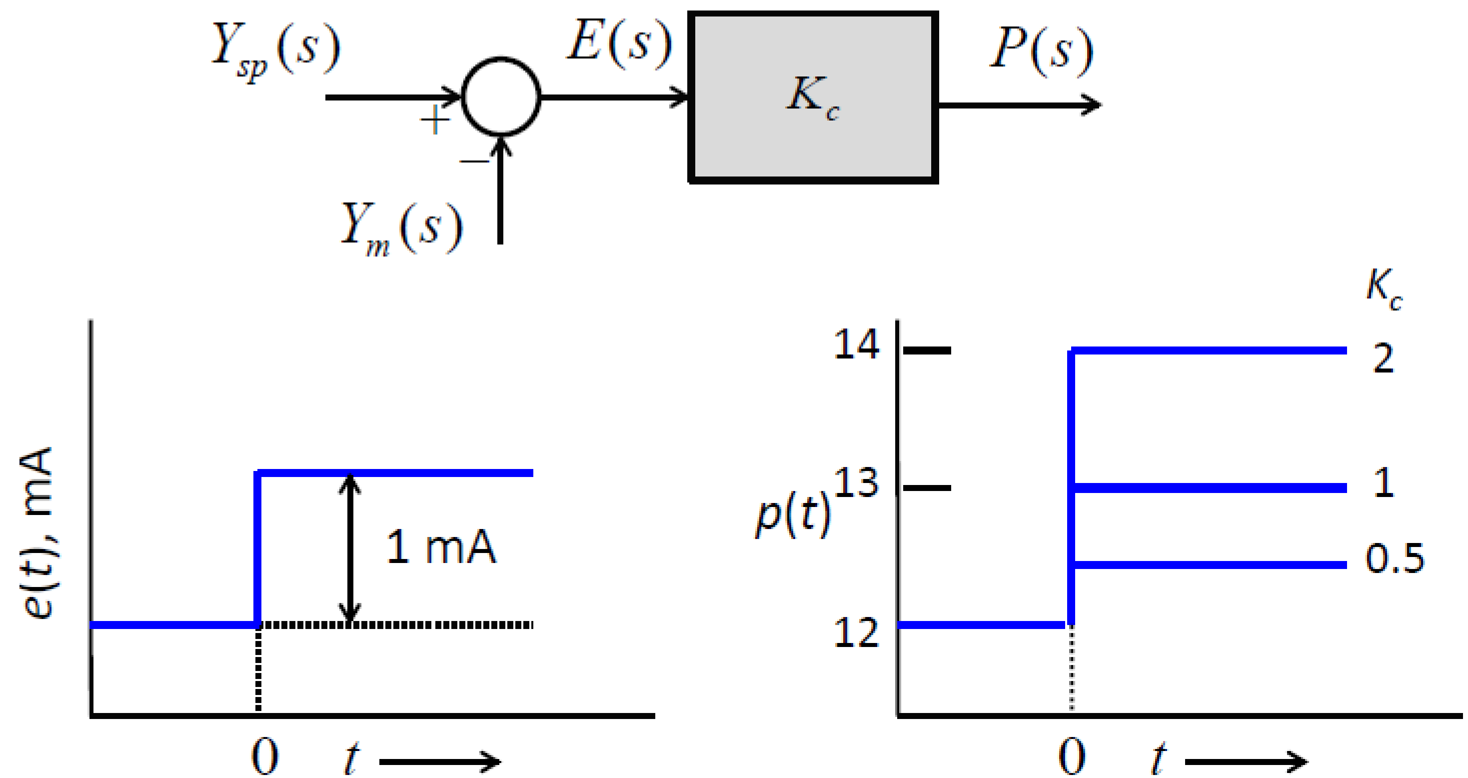
- Proportional controller
  - Output is proportional to the error signal
  - $p(t) = \bar{p} + K_c e(t) \qquad (8-2)$
  - $p(t)$: Controller output, K_c: Controller gain, $\bar{p}$: steady-state value
- Transfer function for proportional controller

$$p'(t) = K_c e(t) \qquad (8-5)$$

- Laplace transform

$$P'(s) = K_c E(s) \quad \text{or} \quad \frac{P'(s)}{E(s)} = K_c \qquad (8-6)$$

Proportional Control (Cont'd)



Proportional Control (Cont'd)

- Proportional control is attractive because of its simplicity
- Disadvantage
  - Steady-state error (or offset) occurs after set-point change or a sustained disturbance
- Example
  - Level control problem

Key Concepts for Proportional Control

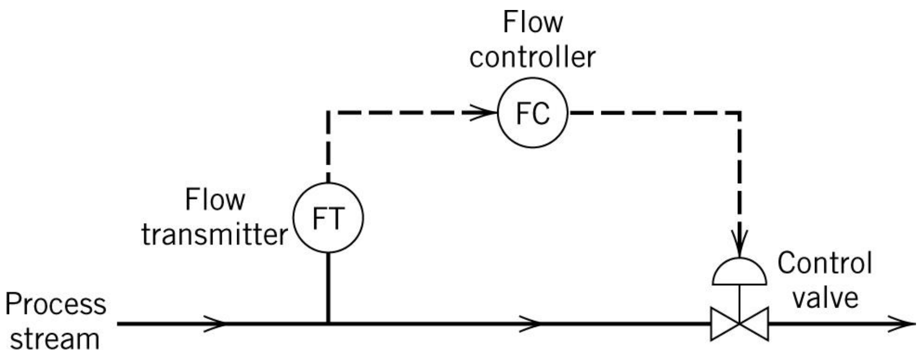
- Proportional band (PB), in %
- $PB \triangleq \frac{100\%}{K_c} \qquad (8-3)$
- Reverse or direct-acting controller
  - K_c can be either positive or negative

$$p(t) = \bar{p} + K_c e(t) \qquad p(t) = \bar{p} + K_c[y_{sp}(t) - y_m(t)]$$

- Direct-acting
  - Output increases $p(t)$ as input increases $Y_m(t)$ $(K_c < 0)$
- Reverse-acting
  - Output increases $p(t)$ as input decreases $Y_{m(t)}$ $(K_c > 0)$

Example

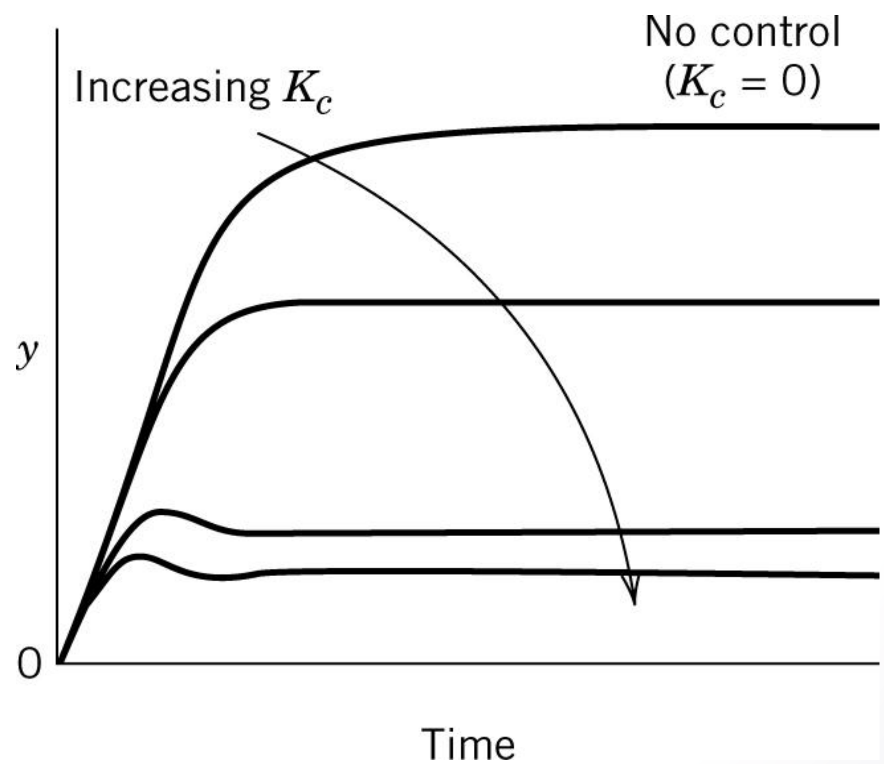
- Flow control loop:



- Assume FT is direct-acting:
  - Should the flow controller direct or reverse action?
    - Air-to-open (fail close) valve ==> Flow rate through the valve increases as the signal to the valve $p(t)$ increases.
    - Air-to-close (fail open) valve ==> ?
- It is extremely important that the controller action is specified correctly.
- General guidelines: The overall product of the gains for all the components in the feedback control should be positive.

Qualitative Effects of Parameters on Performance

- P-Control for Disturbance Tracking: Increasing K_c results in
  - Faster response
  - Reduced offset
  - Increased oscillations
  - Instability



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2. Integral Control

- The controller output depends on the integral of the error signals over time.
- $p(t) = \bar{p} + \frac{1}{\tau_I}\int_0^t e(t^*)dt^*$ $\quad (8-7)$
- $\tau_I \equiv$ reset time (or integral time) – units of time
- Important advantage: **Elimination of offset**
  - When $e \neq 0$, $p(t)$ changes with time until $e(t) = 0$, where p reaches a steady state that causes error to be zero.
- Disadvantage
  - It tends to produce **oscillatory responses** and reduces stability (can be avoided by proper tuning or including derivative action).

Proportional-Integral (PI) Control

- Integral controller is seldom used by itself (as it acts slow).
- Integral control action is normally used in conjunction with proportional control as PI.
- PI controller:

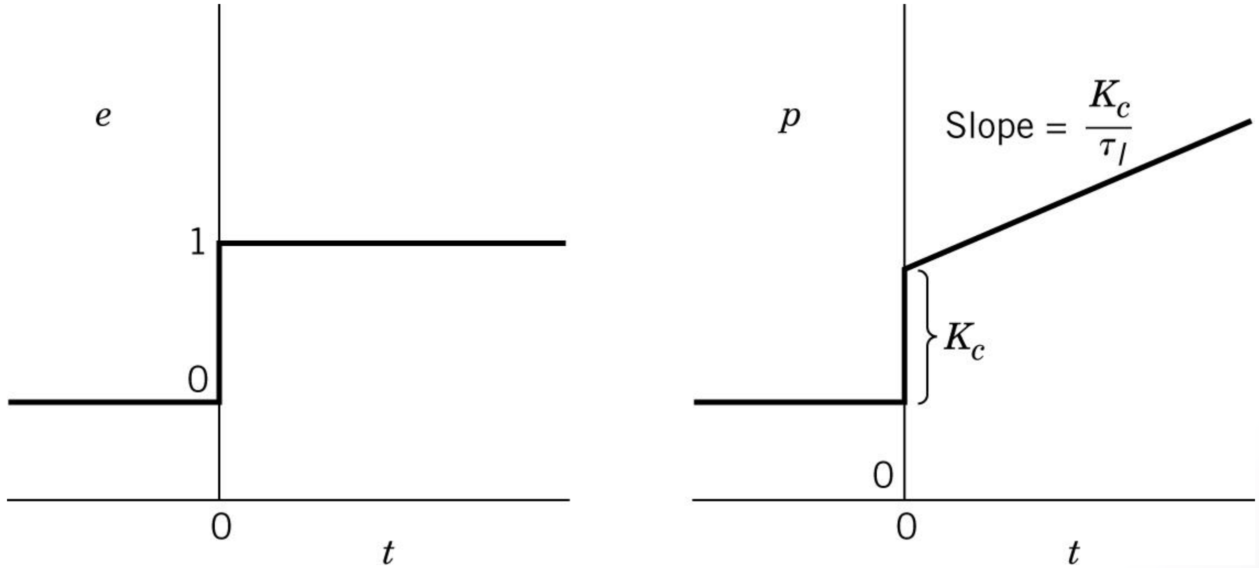
$$p(t) = \bar{p} + K_c\left(e(t) + \frac{1}{\tau_I}\int_0^t e(t^*)dt^*\right) \qquad (8-8)$$

- Transfer function for PI:

$$\frac{P'(s)}{E(s)} = K_c\left(1 + \frac{1}{\tau_I s}\right) \qquad (8-9)$$

PI Controller (Cont'd)

- Response of PI controller to a unit step change in $e(t)$:
  - Controller output changes instantaneously due to P action.
  - Integral action causes the ramp increase in $p(t)$.
  - Integral time: time the controller takes to repeat p action.



Source: Seborg, D. E., Edgar, T. F., & Mellichamp, D. A. (2011). *Process dynamics and control* (2nd ed.)(pp.191). Hoboken, NJ: Wiley.

Key Concepts for Integral Control

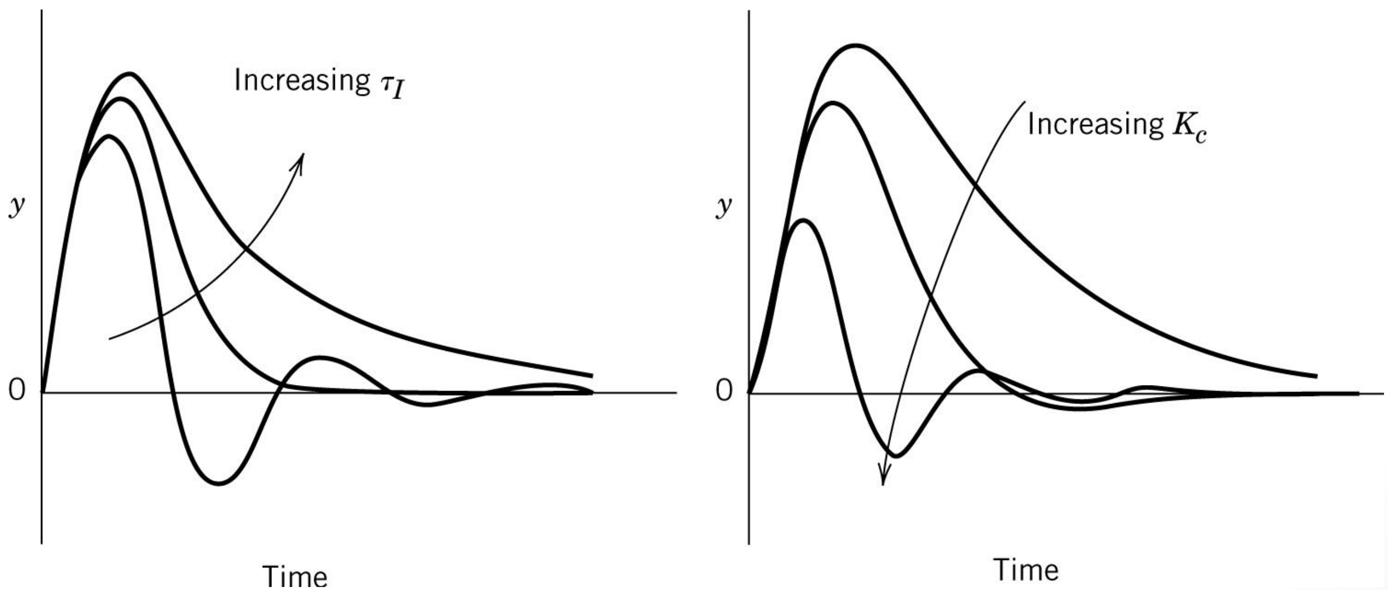
- Reset windup or integral windup:
  - Inherent disadvantage of integral control.
  - Integral mode causes the controller output to change as long as $e(t) \neq 0$.
  - When a sustained error occurs, the integral term becomes quite large & controller output eventually saturates.
  - Further build-up of the integral term while the controller is saturated is referred to as reset windup or integral windup.

Summary of PI Controllers

- Two parameters K_c and τ_I
- "I" action eliminates offset
- Tends to produce oscillatory response
- Reduces the stability

Qualitative Effects of PI Parameters on Performance

- Increasing integral time makes the controller more conservative (sluggish).
- Theoretically, offset will be eliminated for all positive values of integral time.



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3. Derivative Control

- Anticipatory control
  - Anticipates the future behavior of the error signal by considering its rate of change.
  - Tends to stabilize the controlled process.
  - Example: A reactor temperature increases by 10 degrees in 3 mins.
  - P control? I control?
  - Controller output proportional to the rate of change of the error signal:

$$p(t) = \bar{p} + \tau_D \frac{de(t)}{dt} \qquad (8-10)$$

  - In presence of noise (high frequency random fluctuations), derivative of the measured variable will change wildly and derivative action will amplify the noise.

Proportional-Integral-Derivative (PID) Control

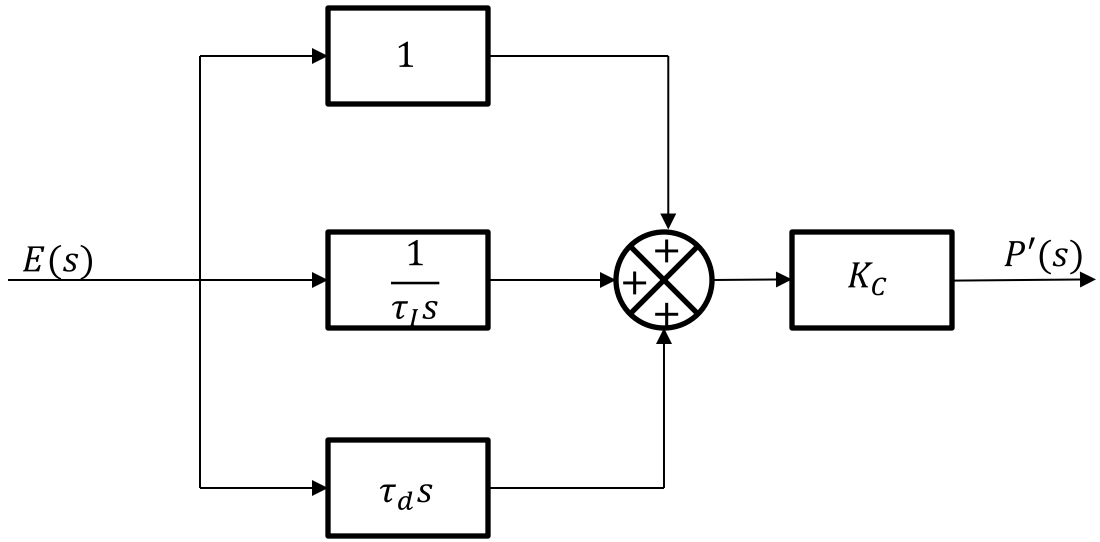
- Combination of the proportional, integral, and derivative control modes as a PID controller.
- Many variations of PID control are used in practice.
- We consider the three most common forms: parallel form, series form, and expanded form of PID control.
- Parallel form of PID control (most commonly used):

$$p(t) = \bar{p} + K_c\left[e(t) + \frac{1}{\tau_I}\int_0^t e(t^*)dt^* + \tau_D\frac{de(t)}{dt}\right] \qquad (8-13)$$

- Corresponding transfer function:

$$\frac{P'(s)}{E(s)} = K_c\left[1 + \frac{1}{\tau_I s} + \tau_D s\right] \qquad (8-14)$$

Standard: Parallel Form of PID Control



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- What if *e*(t) becomes constant?
- P action?
- D action?
- I action?

Series Form of PID Control

- PI and PD operated in series:

$$\frac{P'(s)}{E(s)} = K_c\left(\frac{\tau_I s + 1}{\tau_I s}\right)(\tau_D s + 1)$$

- Commercial versions of the series-form controller have a derivative filter:

$$\frac{P'(s)}{E(s)} = K_c\left(\frac{\tau_I s + 1}{\tau_I s}\right)\left(\frac{\tau_D s + 1}{\alpha\tau_D s + 1}\right) \qquad (8-15)$$

Expanded Form of PID Control

- Expanded form

$$p(t) = \bar{p} + K_c e(t) + K_I \int_0^t e(t^*) dt^* + K_D \frac{de(t)}{dt} \qquad (8-16)$$

- Three gains K_c, KI, KD

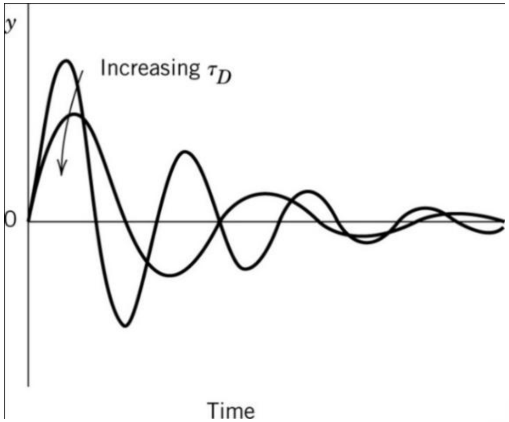
- Expanded form of PID is used in MATLAB

PID Controller

- Three tuning parameters: K_c, τ_I, τ_D
- Better response than PI controller
- P, I, and D mode respectively depends on
  - The present error
  - Accumulation of past error
  - Prediction of future errors

Qualitative Effects of Derivative Time on Performance

- Difficult to generalize the effects of derivative time τ_D.
  - For small values, increasing τ_D tends to improve the response by reducing the maximum deviation, response time, and degree of oscillation.
  - However, if τ_D is too large, measurement noise is amplified and response may become oscillatory.
  - Intermediate value of τ_D is desirable.



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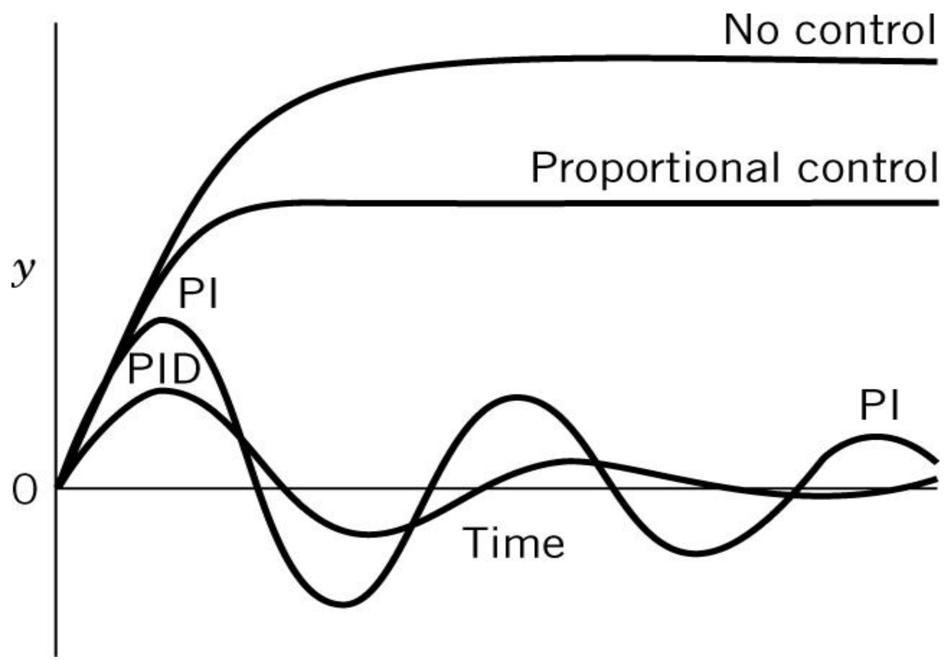
Typical Response of a Feedback Control System

- A step change in a disturbance variable occurs.



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- Actual behavior would depend on the type of controller, controller settings, and process dynamics.

Summary

Below is the summary of the characteristics of the most commonly used controller modes:

- Proportional
  - Simple
  - Inherently stable when properly tuned
  - Easy to tune
  - Experiences offset at steady state
- Proportional plus integral
  - No offset
  - Better dynamic response than reset alone
  - Possibilities exist for instability due to lag introduced

Summary (Cont’d)

- Proportional plus derivative
  - Stable
  - Less offset than proportional alone (use of higher gain possible)
  - Reduces lags, i.e., more rapid response
- Proportional plus integral plus derivative
  - Most complex
  - Rapid response
  - No offset
  - Best control if properly tuned

Review Questions

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Event code

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Chapter 8: Feedback Controllers

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