Enhanced Single-Loop Control Strategies (Advanced Control)

- Cascade Control
- Time-Delay Compensation
- Inferential Control
- Selective and Override Control
Cascade Control

- A disadvantage of conventional feedback control is that corrective action for disturbance does not begin until after the controlled variables deviates from the set-point.

**Example**: Furnace temperature control

![Diagram of furnace temperature control](image)

- **Disturbance**: Oil flow rate
  - Cold oil temperature → satisfactory response

- **Disturbance**: Fuel gas supply pressure (Fuel gas flow)
  - → sluggish response

Conventional feedback control
Another Example: Temperature control of tanks in series

How to improve control performance?

- **Feedforward control**: disturbances have to be measured and a model is required to calculate the controller output
- **Cascade control**: use a secondary measurement and a secondary feedback controller
• **Cascade control**: a primary control loop (TT1 and TC1) and a secondary control loop (TT2 and TC2)
Figure 16.3 Cascade control of an exothermic chemical reactor.
Cascade Control

- **Distinguishing features:**
  1. Two FB controllers but only a single control valve (two controlled variables, two sensors, and one manipulated variable).
  2. Output signal of the "master" controller is the set-point for "slave" controller.
  3. Two FB control loops are "nested" with the "slave" (or "secondary") control loop inside the "master" (or "primary") control loop.

- **Terminology:**
  - slave vs. master
  - secondary vs. primary
  - inner vs. outer
A Furnace Cascade Temperature Control

Primary (outer) control loop

Master controller

TC

Stack gas

Set point

Secondary (inner) Control loop

Slave controller

PC

Furnace

Hot oil

Cold oil

Fuel gas
Block Diagram of Cascade Control System

1: primary loop
2: secondary loop

\[ Y_1 = \text{hot oil temperature} \]
\[ Y_2 = \text{fuel gas pressure} \]
\[ D_1 = \text{cold oil temperature} \]
\[ \text{(or cold oil flow rate)} \]
\[ D_2 = \text{supply pressure of gas fuel} \]
\[ Y_{m1} = \text{measured value of } Y_1 \]
\[ Y_{m2} = \text{measured value of } Y_2 \]
\[ Y_{sp1} = \text{set point for } Y_1 \]
\[ Y_{sp2} = \text{set point for } Y_2 \]

(Furnace Example)
Design Considerations for Cascade Control

- For a cascade control system to function properly, the secondary control loop must respond *faster* than the primary loop.
- The secondary controller is normally a P or PI controller. The primary controller is usually PI or PID.
- First, design $G_{c2}$ for inner loop. *(inside-out)*

\[
\frac{Y_2}{Y_{sp2}} = \frac{G_{c2} G_v G_{p2}}{1 + G_{c2} G_v G_{p2} G_{m2}}
\]
• Then, design $G_{c1}$ for outer loop.

\[
\frac{Y_1}{D_2} = \frac{G_{p1}G_{d2}}{1 + G_{c2}G_vG_{p2}G_{m2} + G_{c1}G_{c2}G_vG_{p2}G_{p1}G_{m1}} \quad (16-5)
\]

\[
\frac{Y_1}{D_1} = \frac{G_{d1}(1 + G_{c2}G_vG_{p2}G_{m2})}{1 + G_{c2}G_vG_{p2}G_{m2} + G_{c1}G_{c2}G_vG_{p2}G_{p1}G_{m1}} \quad (16-8)
\]
Example
Consider the block diagram with the following transfer functions:

\[ G_v = \frac{5}{s+1} \quad G_{p1} = \frac{4}{(4s+1)(2s+1)} \quad G_{p2} = 1 \]

\[ G_{d2} = 1 \quad G_{m1} = 0.05 \quad G_{m2} = 0.2 \quad G_{d1} = \frac{1}{3s+1} \]

Primary loop: PI
Secondary loop: P

Great improvement
Slight improvement
Time Delay Compensation (Smith Predictor)

- The presence of time delay in a process limits the performance of a conventional feedback control system.
  - A time delay will adversely affect closed-loop stability.

**Example 16.2**

Compare the set-point responses for a second-order process with a time delay and without the delay. The transfer function is

\[
G_p(s) = \frac{e^{-\theta s}}{(5s + 1)(3s + 1)}
\]

Assume \(G_m = G_v = 1\). Use the following PI controllers.

For \(\theta = 0\), \(K_c = 3.02\), \(\tau_I = 6.5\).

For \(\theta = 2\), \(K_c = 1.23\), \(\tau_I = 7.0\).

(the controller gain must be reduced to meet stability requirements)
• The response of the closed-loop system will be sluggish compared to that of the control loop with no time delay. (not only 2 min.)
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Block Diagram of Smith Predictor

Model \( \tilde{G} = \tilde{G}^* e^{-\theta s} \)

\[
E' = E - \tilde{Y}_1 = Y_{sp} - \tilde{Y}_1 - (Y - \tilde{Y}_2)
\]  

(16–19)

If the process model is perfect and the disturbance is zero, then \( \tilde{Y}_2 = Y \)

\[
E' = Y_{sp} - \tilde{Y}_1
\]

(16–20)

For this ideal case the controller responds to the error signal that would occur if no time delay were present.
Assuming there is no model error \( \left( \tilde{G} = G \right) \), the inner loop has the effective transfer function

\[
G_c' = \frac{P}{E} = \frac{G_c}{1 + G_c G* \left(1 - e^{-\theta s}\right)}
\]  \hspace{1cm} (16 - 21)
For no model error:

\[
\frac{Y}{Y_{sp}} = \frac{G'_c G^* e^{-\theta s}}{1 + G'_c G^* e^{-\theta s}} = \frac{G_c G^* e^{-\theta s}}{1 + G_c G^*} = \frac{G_c G}{1 + G_c G^*}
\]

By contrast, for conventional feedback control

\[
\frac{Y}{Y_{sp}} = \frac{G_c G}{1 + G_c G} = \frac{G_c G^* e^{-\theta s}}{1 + G_c G^* e^{-\theta s}}
\] (16–23)

The Smith predictor has the advantage of eliminating the time delay from the characteristic equation. Unfortunately, this advantage is lost if the process model is inaccurate.

(It can still provide improvement if the model parameters are within about ±30% of the actual values)
**Closed-loop set-point responses**

Smith predictor (SP) has the same controller settings with conventional feedback PI controller. \((K_c = 3.02, \tau_I = 6.5)\)

- The responses are identical, except for the initial time delay.
How about the disturbance response?

- The Smith predictor generally is beneficial for handling disturbance. However, under certain conditions, a conventional PI controller can provide better regulatory control than SP.

\[
\theta=2
\]

\[
\frac{Y}{D} = \frac{G_d \left[ 1 + G_c G^* \left( 1 - e^{-\theta s} \right) \right]}{1 + G_c G^*}
\]

**Figure 16.11** A comparison of disturbance changes for the Smith predictor and a conventional PI controller.
Inferential Control

• **Problem:** Controlled variable cannot be measured or has large sampling period.

• **Possible solutions:**
  1. Control a related variable (e.g., temperature instead of composition).
  2. **Inferential control:** Control is based on an estimate of the controlled variable.
     • The estimate is based on available measurements.
       – **Examples:** empirical relation, neural network
     • Modern term: *soft sensor*
Inferential Control with Fast and Slow Measured Variables

*Soft sensor block diagram*

( Note: $X$ and/or $Y$ can be used for control )
Selective Control & Override Control

• For every controlled variable, it is very desirable that there be at least one manipulated variable.

• But for some applications,

\[ N_C > N_M \quad (N_C \neq N_M) \]

where:

\[ N_C = \text{number of controlled variables} \]

\[ N_M = \text{number of manipulated variables} \]

• **Solution:** Use a *selective control system* or an *override*.
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Selectors

- Selectors are used to improve the control performance as well as to protect equipment from unsafe operating conditions.

  - **Low selector:**

    ![Diagram of a low selector](image1)
    
    $Z = \text{Minimum of } X \text{ and } Y$

  - **High selector:**

    ![Diagram of a high selector](image2)
    
    $Z = \text{Maximum of } X \text{ and } Y$

  - **Median selector:**

    - The output, $Z$, is the median of an odd number of inputs
      (useful when redundant sensors are used to measure a single process variable)
Example: High Selector Control System

Control of a reactor hotspot temperature

- multiple measurements
- one controller
- one final control element

Determine the hotspot temperature
Overrides

- An *override* is a special case of a selective control system
- One of the inputs is a numerical value, a limit.
- Used when it is desirable to limit the value of a signal (e.g., a controller output).

*Temperature control of a heater*
A selective control system to handle a sand/water slurry
(regulate the level and exit flow rate)

2 measurements, 2 controllers, 1 final control element

Keep flow rate above its minimum value

Slurry in

Holding tank

Variable speed pump

Slurry out (to tailings pond)
Block Diagram for the Selective Control Loop

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Split-Range Control

- Multiple final control elements or multiple controllers

Reactor temperature control (both heating and cooling are used)

Figure 16.14 Split range control:
(a) control loop configuration, 
(b) valve position–controller output relationship.