Traditional Advanced Control Approaches – Feedforward, Cascade and Selected Control

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2-1 Feed Forward Control (FFC)

- Block Diagram
- Design of FFC controllers
- Examples
- Applications

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Feedback control loop

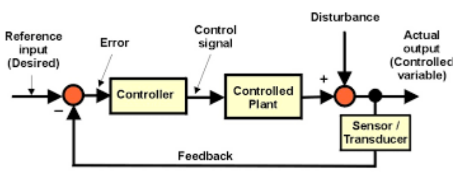

Fig.15: Feedback control system

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Example: Heat exchanger

Operational objective:

(i)Keep temperature of the effluent at a desired value T_s

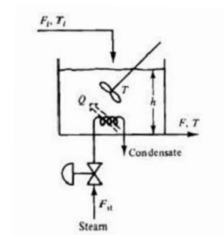

Figure 1.1 Stirred tank heater.

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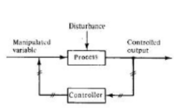
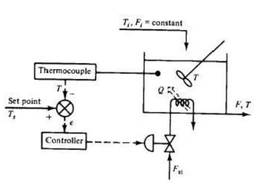
Feedback Control action





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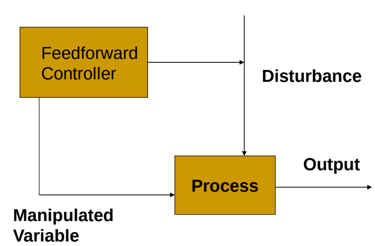
Feedforward Control



Have theoretical potential for perfect control

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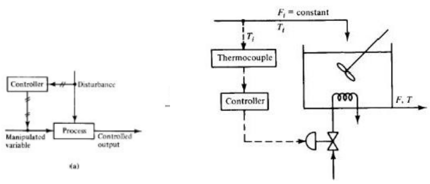
Feedforward action



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Feedforward Control

- Advantages
  - Corrective action is taken as soon as disturbances arrives.
  - Controlled variable need not be measured.
- Disadvantages
  - **No corrective action until disturbance has affected the output. Perfect control is impossible.**
  - Nothing can be done about known process disturbance
  - Load variable must be measured
  - A process model is required
  - Errors in modeling can result in poor control

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Feedback acts **after** in a **compensatory manner**

while

Feedforward acts **beforehand** in an **anticipatory manner**

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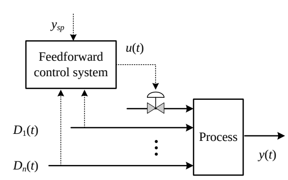
Feedforward Concept for multiple disturbance



$D_1(t)$, …, $D_n(t)$ represent some measurable disturbances to the controlled variable

Idea: to compensate for some *measurable* disturbances before they affect the controlled variable.

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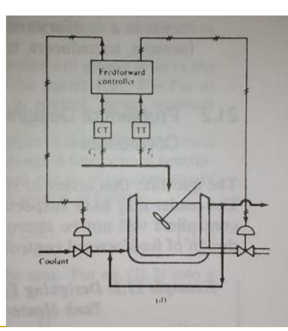
Example: CSTR



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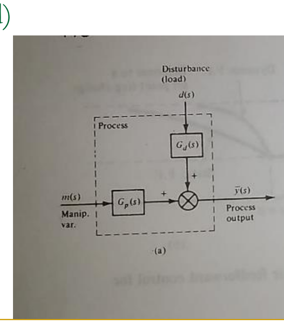
Design Procedures (Block diagram Method)



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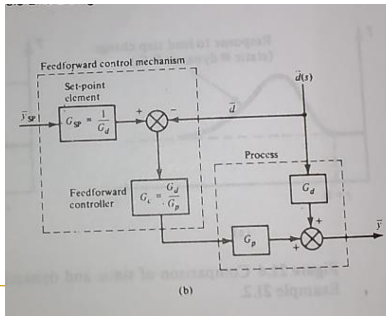
Feedforward mechanism



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Remarks

- Loop retains all the components of a feedback system.
- Not a conventional feedback controller (P,PI,PID), but a special purpose conmuting system.
- Design depends heavily on the understanding of the process models (G_p,G_d)

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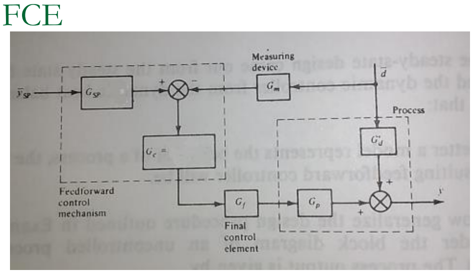
System with addition of sensor and FCE



- $Y=G_pG_fG_cG_{SP}y_{SP} +[G_d-G_pG_fG_cG_m]d$

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Design:

- 1. Disturbance rejection
  Get Gc
- 2.Set point tracking
  Get G_{SP}

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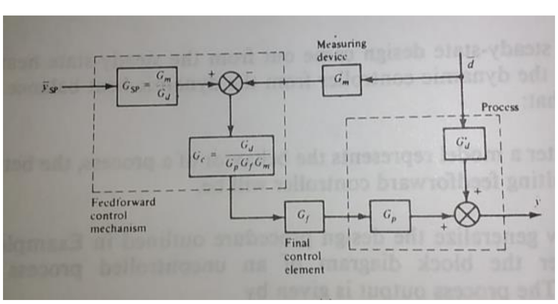
System with addition of sensor and FCE



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Examples of designing from system models: 1. STR

Objective : To maintain temperature T at T_{SP}

Assume Fi does not change ; Fi=F

System

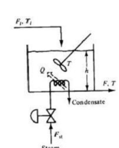

Figure 1.1 Stirred tank heater.

Equations

$$A\frac{dh}{dt} = F_i - F$$

$$Ah\frac{dT}{dt} = F_i(T_i - T) + \frac{Q}{\rho c_p}$$

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(i)Steady state feed forward controller

$$0 = F_i(T_i - T) + \frac{Q}{\rho c_p}$$

$$T = T_i + \frac{Q}{F_i \rho c_p}$$

- Design equation is the equation that relates the controlled variable to the manipulated variable:

$$Q = F_i \rho c_p (T_{SP} - T_i)$$

- Eq. shows hoe Q must change in the presence of disturbance or set point changes

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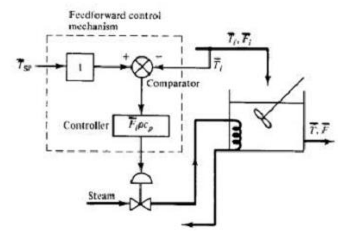
Block diagram for steady state design



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FF-FB Control

- FF disadvantages:
  - Requires identification of all disturbances and their direct measure
  - Changes in process parameters cannot be compensated as their impact is not detected
  - Requires a very good model for the process.
- FB can compensate many of these drawbacks and can improve the closed loop stability,
- So combined system will be much superior

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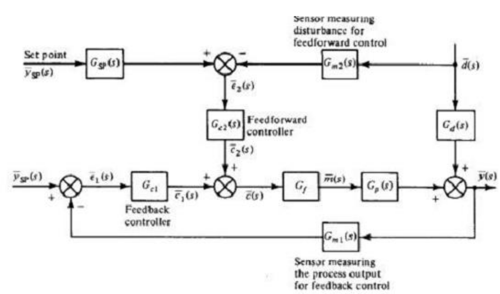
General block diagram



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Design of the loop

$$\overline{y} = G_p\overline{m} + G_d\overline{d}$$

$$\overline{m} = G_f\overline{c} = G_f(\overline{c}_1 + \overline{c}_2) = G_fG_{c1}\overline{\epsilon}_1 + G_fG_{c2}\overline{\epsilon}_2$$

$$\overline{m} = G_fG_{c1}(\overline{y}_{SP} - G_{m1}\overline{y}) + G_fG_{c2}(G_{SP}\overline{y}_{SP} - G_{m2}\overline{d})$$

- Final closed loop system equation is:

$$\overline{y} = \frac{G_pG_f(G_{c1} + G_{c2}G_{SP})}{1 + G_pG_fG_{c1}G_{m1}}\overline{y}_{SP} + \frac{G_d - G_pG_fG_{c2}G_{m2}}{1 + G_pG_fG_{c1}G_{m1}}\overline{d}$$

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Points to note:

- The stability of the CL system is determined by the roots of the characteristic equation.

$$1 + G_pG_fG_{c1}G_{m1} = 0$$

- Which depends in the TF of feedback loop only. So feedforward will not add any effect on stability characteristics.

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- The transfer functions of FF loops G_{c2} and G_{sp} design remains the same for that with single FF loop
- If any of G_p,G_d,G_f,G_{m2} are known approximately,(not accurately) then:

$$G_d - G_p G_f G_{c2} G_{m2} \neq 0 \quad \text{and/or} \quad G_p G_f G_{c2} G_{SP} \neq 1$$

- Then FF don't provide sufficient control action and FB is activated.

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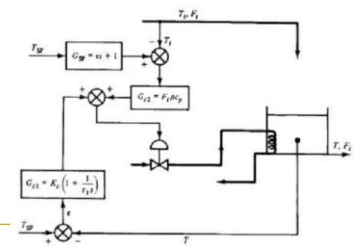
Examples of designing FF-FB controller : 1. STR

Objective : To maintain temperature T at T_{SP}

Assume Fi does not change ; Fi=F



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When to use Feedforward ?

- Feedback control is unsatisfactory
- Disturbance can be measured and compensated for
- Frequency of disturbance variations are comparable to frequency of oscillation of the system
- Output variable cannot be measured.
- There are large time delays in the system

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2 Cascade Control

- Introduction and Block Diagram
- Design Considerations
- Applications

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Cascade:

- One manipulated variable and more than one measurement.
- Single manipulation can be used to control only one input.
- Cascade control is mainly used to achieve fast rejection of disturbance before it propagates to the other parts of the plant.
- The simplest cascade control system involves two control loops (inner and outer)

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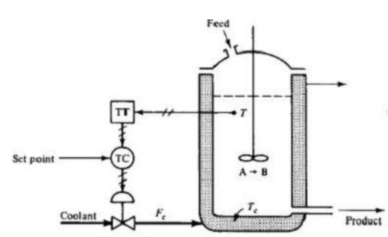
Illustrative Example: Temperature control of CSTR; simple feedback



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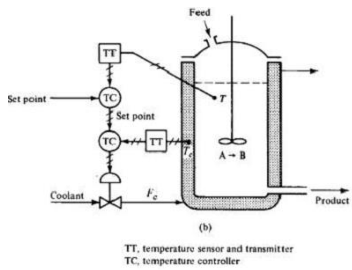
Illustrative Example: Temperature control of CSTR; Cascade control



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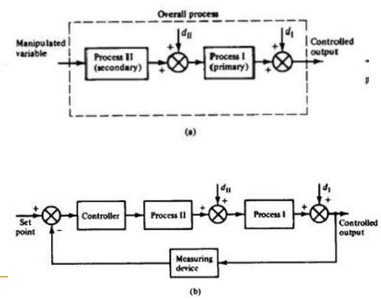
Block diagram representation:



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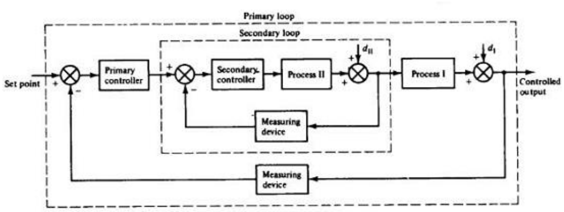
Cascade block



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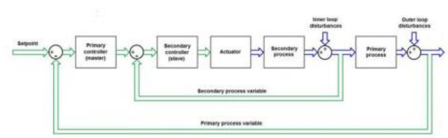
Elements of cascade control



- Two controllers, two sensors, and one actuator acting on two processes in series.
- A primary or master serves as the setpoint for a secondary or slave controller.

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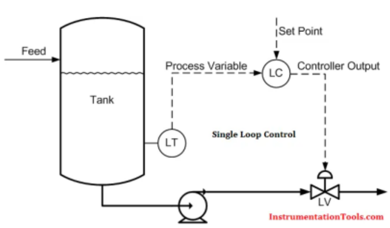
Develop a cascade controller for level process where flow in the secondary process.



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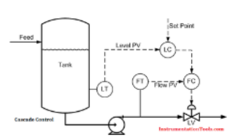
Develop a cascade controller for level process where flow in the secondary process.



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- The inner loop functions like a traditional feedback control system with a setpoint, a process variable, and a controller acting on a process by means of an actuator.
- The outer loop does the same except that it uses the entire inner loop as its actuator.

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Requirements

- The inner loop has influence over the outer loop. The actions of the secondary controller must affect the primary process variable in a predictable and repeatable way.
- The inner loop is faster than the outer loop. The secondary process must react to the secondary controller's efforts at least three or four times faster than the primary process reacts to the primary controller.
- The inner loop disturbances are less severe than the outer loop disturbances.

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Challenges

- Most notably, the extra sensor and controller tend to increase the overall equipment costs. Cascade control systems are also more complex than single-measurement controllers.
- the tuning procedure is straightforward: tune the secondary controller first, then the primary controller using the same tuning tools applicable to single-measurement controllers.

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Principal Advantages and Disadvantages

- Advantages
  - Disturbances in the secondary loop are corrected by secondary controllers
  - Response of the secondary loop is improved, thus increasing the speed of response of the primary loop
  - Gain variations in secondary loop are compensated by secondary loop
- Disadvantages
  - Increased cost of instrumentation
  - Need to tune two loops instead of one
  - Secondary variable must be measured

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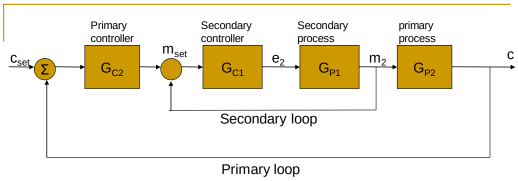
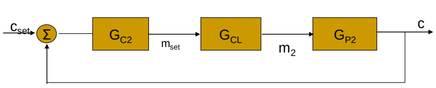


$$\frac{m_2}{m_{set}} = \frac{G_{C1}G_{P1}}{1+G_{C1}G_{P1}} = G_{C2}$$



$$\frac{c}{c_{set}} = \frac{G_{C2}G_{CL}G_{P2}}{1+G_{C2}G_{CL}G_{P2}}$$

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Selective Control Systems

- Ratio Control
- Inferential control
- Split range control
- MPC
- IMC etc..
  - Change from one controlled (CV) or manipulated variables (MV) to another

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Ratio control

- Special control where two disturbances are measured and held in a constant ratio to each other.
- To control the ratio of flow rates of two streams.
- Both are measured, One is controlled.
- Controlled flow: That is controlled.
- Wild flow: Not controlled.

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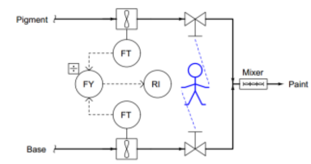
Ratio Control

- A simple example of ratio control is in the production of paint, where a base liquid must be mixed with one or more pigments to achieve a desired consistency and color. A manually controlled paint mixing process, similar to the hot and cold water valve "process" in some home showers, is shown here. Two flowmeters, a ratio calculating relay, and a display provide the human operator with a live measurement of pigment-to-base ratio:



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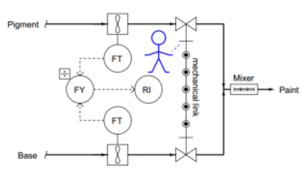
- One alteration we could make to this mixing system is to link the two manual control valve handles together in such a way that the ratio of base to pigment was mechanically established.
- All the human operator needs to do now is move the one link to increase or decrease mixed paint production:



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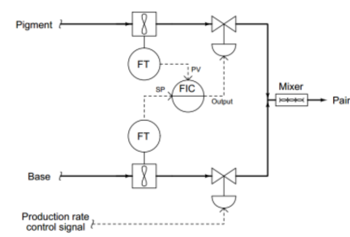

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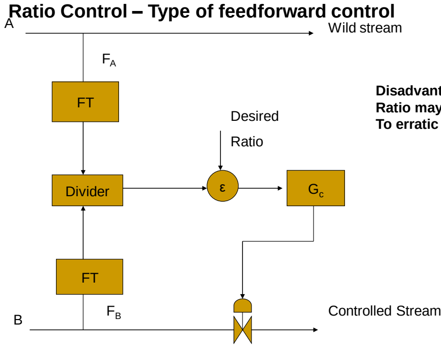
Ratio Control – Type of feedforward control



Disadvantage:
Ratio may go
To erratic

However, one stream in proportion to another. Use if the ratio must be measured and displayed

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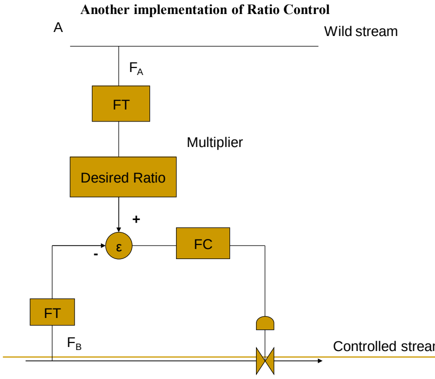
Another implementation of Ratio Control



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SELECTIVE CONTROL ALOGORITHMS

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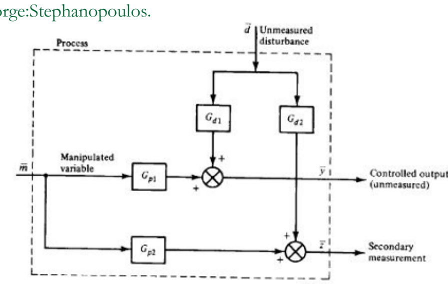
Inferential control

Chapter 22: Adaptive and inferential control system, George:Stephanopoulos.



$$\bar{y} = G_{p1}\bar{m} + G_{d1}\bar{d}$$
$$\bar{z} = G_{p2}\bar{m} + G_{d2}\bar{d}$$

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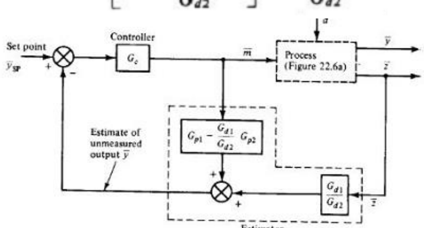
$$\bar{d} = \frac{1}{G_{d2}}\bar{z} - \frac{G_{p2}}{G_{d2}}\bar{m}$$

$$\bar{y} = \left[G_{p1} - \frac{G_{d1}}{G_{d2}}G_{p2}\right]\bar{m} + \frac{G_{d1}}{G_{d2}}\bar{z}$$



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Adaptive control system:

Chapter 22: Adaptive and inferential control system, George Stephanopoulos.

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Introduction

- "To adapt" means to change a behavior to conform to new circumstances.
- An adaptive controller that can modify its behavior in response to the changes in dynamics of the processes and the disturbances acting on the process.

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Introduction

- An adaptive controllers are those with adjustable parameters and a mechanism for adjusting the parameters.
- The parameters are adjusted to compensate for the changes in dynamics of the plant and the disturbances acting on the plant.
- The controller becomes nonlinear because of the parameter adjustment mechanism

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Why adaptive controllers?

- Plant non-linearity
- Nonstationary process

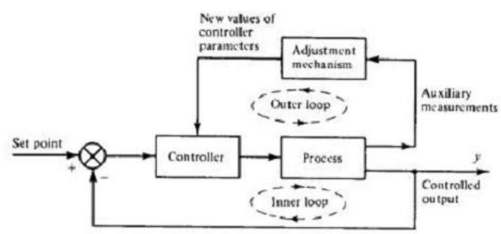
Circumstances under which adaptive control can be preferred:

- it is convenient to control a plant with the available conventional PID controllers.
- Some circumstances under which the adaptive controllers can perform better than the conventional PID controllers are:
- Change in plant transfer function due to variations in the environment, the size and properties of the raw materials, wear & tear of certain components.
- Stochastic disturbances (disturbances whose characteristics/behavior are unpredictable)

Objective of adaptive controllers

- Not to maintain a set point.
- Maintain an Objective function/ Criteria which will guide the adaptation mechanism to the best adjustment of controller parameters.

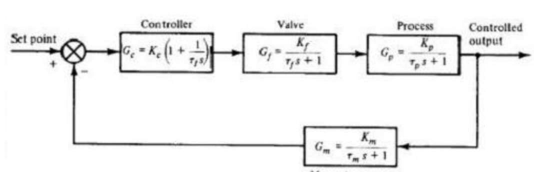
Programmed or scheduled adaptive controllers



Description

- An adaptive control system can be thought of as having two loops.
- One loop is a normal feedback with the process and the controller.
- The other loop is the parameter adjustment loop.
- The parameter adjustment loop (comparable to feedforward compensation) is usually slower than the normal feedback loop.

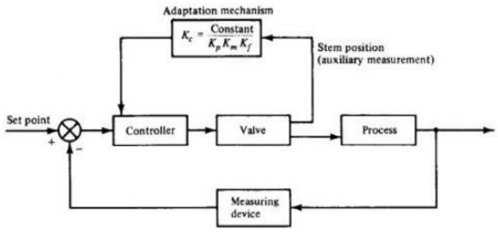
(i)Gain scheduling adaptive controllers



$$K_{overall} = K_p K_m K_c K_f = \text{constant}$$

$$K_c = \frac{\text{constant}}{K_p K_m K_f}$$

i)Gain scheduling adaptive controllers



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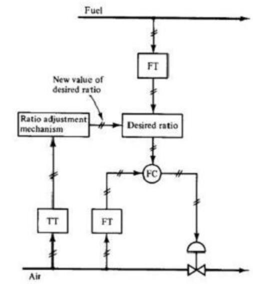
(ii)Programmed adaptive control: Example: Combustion system



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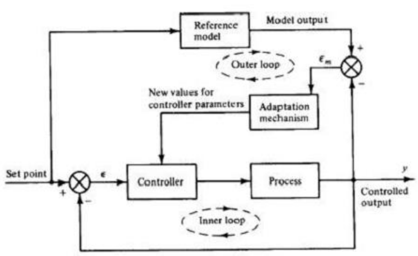
Model reference adaptive Control (MRAC)



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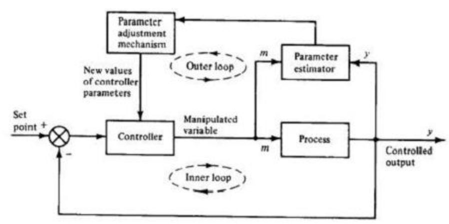
Self tuning regulator (STR)



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Split range control

- One measurement only and more than one manipulated variables.
- One control signal is split into several parts, each affecting one of the available manipulations.
- We control the same output by coordinating the actions of several manipulated variables

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Split range Controller

- Control valves configured to follow the command of the same controller are said to be split-ranged, or sequenced.
- A configuration in which, from a single input signal, two or more signals are generated or two or more final control elements are actuated, each responding consecutively, with or without overlap, to the magnitude of the input signal.
- Split-ranged control valves may take different forms of sequencing. A few different modes of control valve sequencing are commonly seen in industry: **complementary, exclusive, and progressive**.

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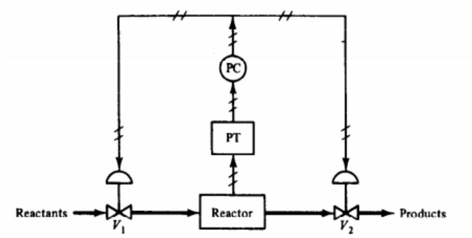
Split range control.

Eg: Control of a chemical reactor



(a)

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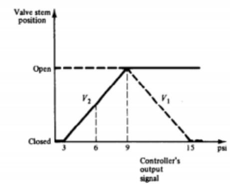

(b)

TABLE 20.1
OUTPUT SIGNAL AND VALVE COORDINATION

Controller's output signal	Valve V_1 stem position	Valve V_2 stem position
3 psig	Open	Closed
9 psig	Open	Open
15 psig	Closed	Open

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Eg.2 Pressure control in a steam header

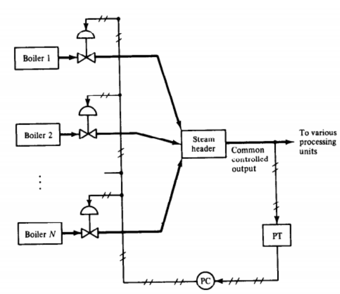

Figure 20.11 Steam header with split-range control.

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Dead time compensator (Smith predictor)

- Delay in normal feedback loops due to :
  - Transportation of fluids over long distance.
  - Sampling time for measuring device
  - Time for valve to develop actuating signal
  - Time for human controller to think and take action
- Problems due to this:
  - Disturbance not be detected till some time
  - Control action at a time would be inadequate.
  - Control action may take time to effect the process.

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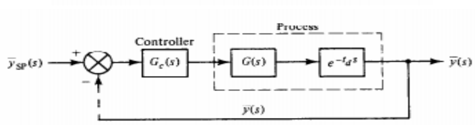
Dead time Compensation/smith predictor

$$G_p(s) = G(s)e^{-t_d s}$$

$$\bar{y}(s) = G_c(s)[G(s)\, e^{-t_d s}]\, \bar{y}_{SP}(s)$$



(a)

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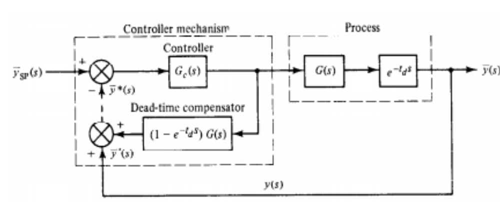
$$\bar{y}^*(s) = G_c(s)G(s)\bar{y}_{SP}(s) \qquad (19.2)$$

This is possible if in the open-loop response $\bar{y}(s)$ we add the quantity

$$\bar{y}'(s) = (1 - e^{-t_d s})G_c(s)G(s)\bar{y}_{SP}(s) \qquad (19.3)$$

It is easy to verify that

$$\bar{y}'(s) + \bar{y}(s) = \bar{y}^*(s)$$



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- y'(s) is taken as a simple local loop around the controller called dead-time compensator or smith predictor.
- Dead time compensator predicts the delayed effect that the manipulated variable will have on process output.
- If models are not accurately known, then approximated models can be used.

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$$\bar{y}^*(s) = \bar{y}(s) + \bar{y}'(s)$$
$$= [G_c G e^{-t_d s} + (1 - e^{-t'_d s}) G_c G'] \bar{y}_{SP}(s)$$

$$\bar{y}^*(s) = G_c[G' + (G e^{-t_d s} - G' e^{-t'_d s})] \bar{y}_{SP}(s)$$

(a) *Only for perfectly known processes will we have perfect compensation (i.e., for $G = G'$ and $t_d = t'_d$).*
(b) *The larger the modeling error [i.e., the larger the differences $(G - G')$ and $(t_d - t'_d)$], the less effective is the compensation.*
(c) *The error in estimating the dead time is more detrimental for effective dead-time compensation [i.e., $(t_d - t'_d)$ is more crucial than $(G - G')$], because of the exponential function.*

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INTERNAL MODEL CONTROL

- is based on an accurate model of the process, leads to the design of a control system that is stable and robust.
- In applying the IMC method of control system design, the following information must be specified:
  - Process model
  - Model uncertainty
  - Type of input (step, ramp, etc.)
  - Performance objective (integral square error, overshoot, etc.)

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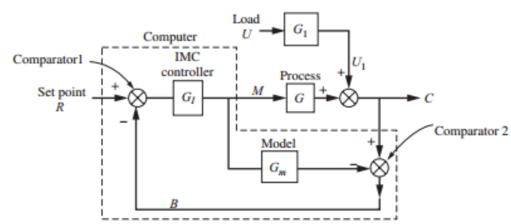
Internal model control



(a)

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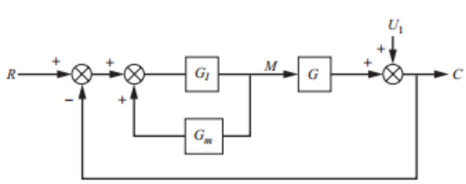
Rearrranged block

(a)



(b)

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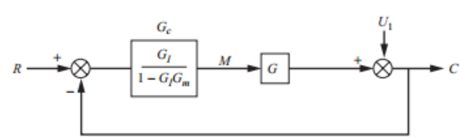
Structure equivalent to conventional control.



(c)

$$G_c = \frac{G_I}{1 - G_I G_m} \qquad C = U_1 + \frac{G G_I}{1 + G_I (G - G_m)} (R - U_1)$$

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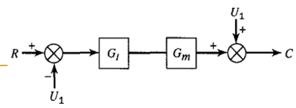
- If the model exactly matches the process (i.e., Gm = G), the only signal entering comparator U1 . (The signals from G and Gm are equal and cancel each other in going through comparator 2.)
- Since Ut is not the result of any processing by the transfer functions in the forward loop, Ut is not a feedback signal but an independent signal
- In fact, there is no feedback when G = Gm and we have an open-loop system.
- In this case the stability of the control system depends only on GI and G,. If GI and G, are stable, the control system is stable.



- Ideally, we should like to have C track *R* without lag when only a set-point change occurs
- For that $G_IG = 1$ or since G = Gm, we may write $G_IGm = 1$.
  Solving for G_I gives

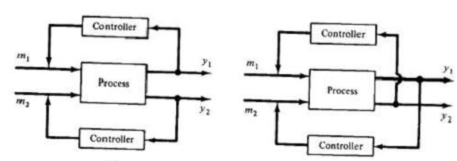
$$G_I = 1/G_m$$

- IMC controller should be the inverse of the transfer function of the process model.

Introduction to multivariable control

- Design questions for multivariable control
  - What are control objectives?
  - Wht outputs should be measured?
  - What inputs should be measured?
  - Manipulated varibales to be used
  - What configuration of control loops to be used.

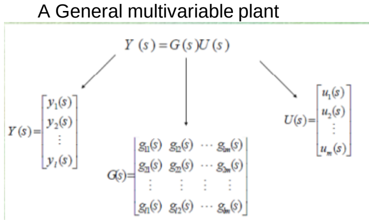
- **For a system with n C.V and n M.V there are n! different loop configurations**



Alternative loop configurations for a 2 × 2 process.

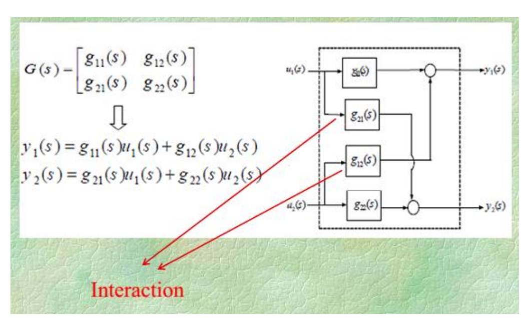
Introduction to multivariable control

- MIMO systems are considered as multivariable systems
  A General multivariable plant

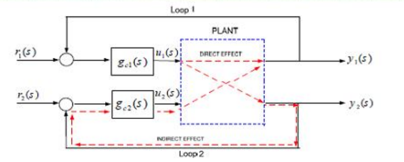


- Why they are different from SISO?
  Since of interaction and design procedure.

Interaction



Interaction



Assume that the plant is under tight control. A change is made in the first set point. The following key observations are made:

- The Direct Effect: The first controller will get the first output to the desired set point.
- The Indirect Effect: The first controller will disturb the second output and the second controller attempts to reject its effects. But changes in the second controller effects the first loop performance.

INTERACTION BETWEEN TWO CONTROL LOOPS!

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Assignment

- Take a 2x2 MIMO system and analyze the practical implementation of the best control loop for the process.

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