Spring 2019

數位控制系統

Digital Control Systems

DCS-33
Discretized Controller – Discrete Design

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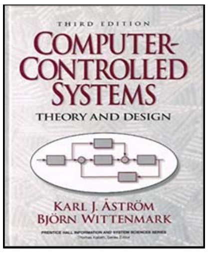
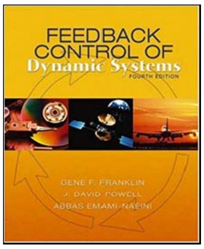
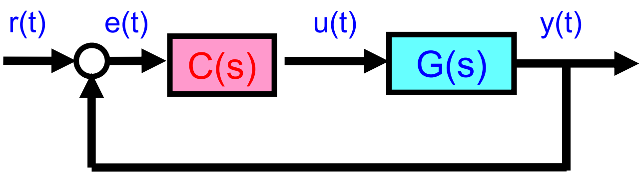
NTU-EE

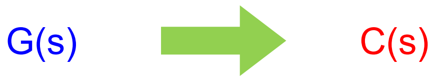
Feb19 – Jun19



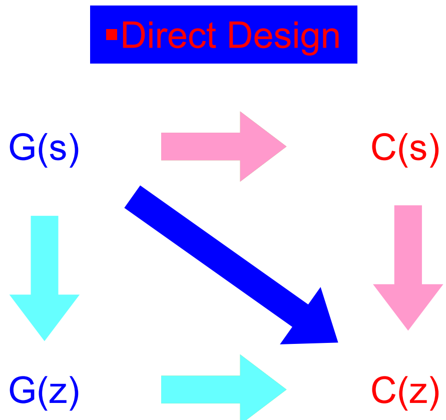


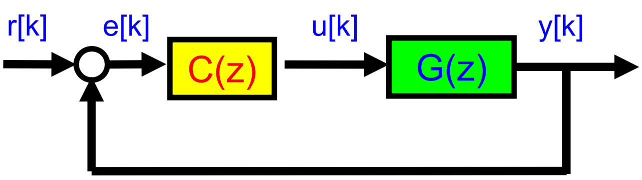
Introduction: CT and DT Plant-Controller

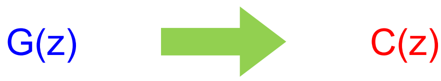




- Discrete Design
  - Transform CT plant into DT plant
  - By DT plant, design DT controller
- Emulation
  - By CT plant, design CT controller
  - Transform CT controller into DT controller







Basic Design Concept

- Basic principles of low-order controller design

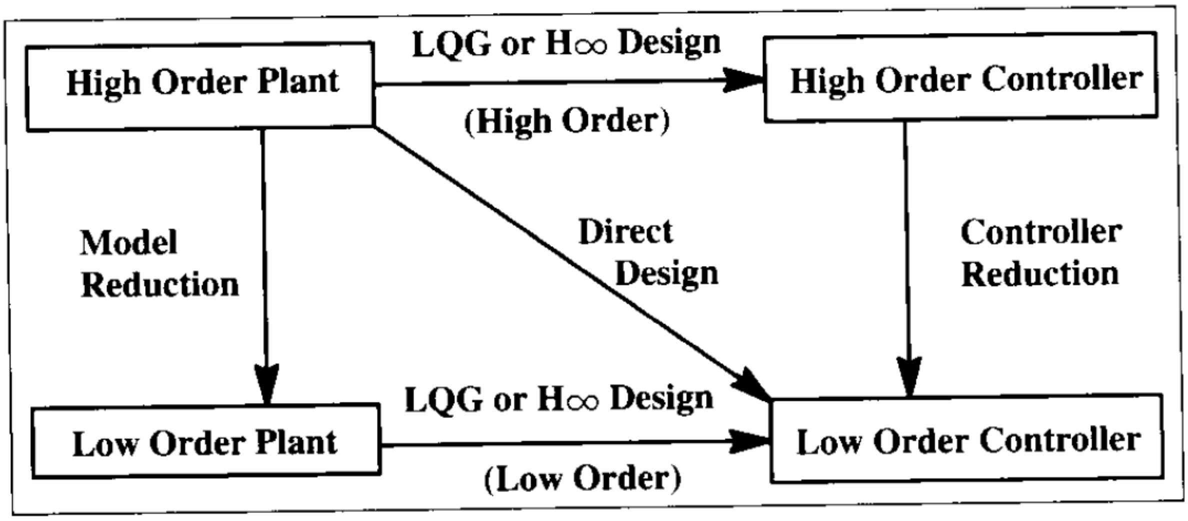


Fig. 1. Basic principles of low order controller design.

B.D.O. Anderson, "Controller Design: Moving from Theory to Practice," IEEE Control Systems Magazine, 13(4), pp. 16-25, Aug. 1993

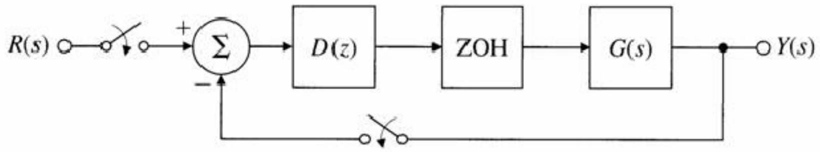
Anderson 1993

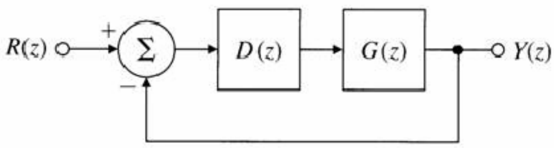
Introduction: CT and DT Plant-Controller

- Study in Digital Control Systems
  - Controller Design of Digital Control Systems
    - **Design Process**
      - > Discrete Design:
        - » CT plant -> DT plant -> DT controller
      - > Emulation:
        - » CT plant -> CT controller -> DT controlle
      - > Direct Design: (B.D.O. Anderson, 1992 Bode Prize Lecture)
        - » CT plant -> DT controller

- Discrete Design
  - By Transfer Function
  - By State Space
- Design by Emulation
  - Tustin's Method or bilinear approximation
  - Matched Pole-Zero method (MPZ)
  - Modified Matched Pole-Zero method (MMPZ)
  - Digital PID-Controllers
- Techniques for Enhancing the Performance

- The Exact Discrete Equivalent:





$$G(z) = (1 - z^{-1}) \mathcal{Z} \left\{ \frac{G(s)}{s} \right\}$$

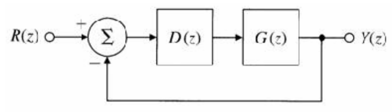
$$\Rightarrow \frac{Y(z)}{R(z)} = \frac{D(z)G(z)}{1 + D(z)G(z)}$$

Franklin et al. 2002

Discrete Design – Transfer Function

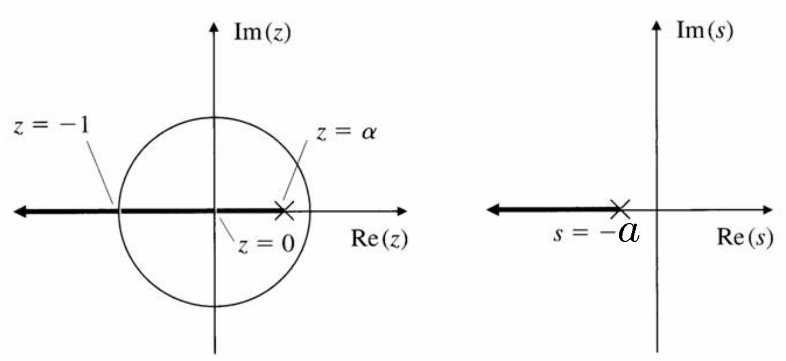
- **Discrete Root Locus:** $G(s) = \dfrac{a}{s+a}$ & $D(z) = K$

$$\Rightarrow \quad G(z) = (1 - z^{-1}) \mathcal{Z} \left\{ \frac{a}{s(s+a)} \right\}$$



$$= (1 - z^{-1}) \left[\frac{(1 - e^{-ah}) z^{-1}}{(1 - z^{-1})(1 - e^{-ah} z^{-1})} \right]$$

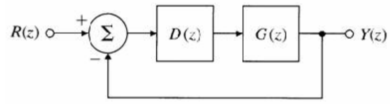
$$= \frac{1 - e^{-ah}}{z - e^{-ah}} \qquad \alpha = e^{-ah}$$



Franklin et al. 2002

Discrete Design – Transfer Function

- **Feedback Properties:**



  - Proportional: $u[k] = K\, e[k] \quad \Rightarrow \quad D(z) = K$
  - Derivative: $u[k] = K\, T_D \left[e[k] - e[k-1] \right]$

$$\Rightarrow \quad D(z) = K\, T_D \left(1 - z^{-1} \right) = k_D \frac{z-1}{z}$$

  - Integral: $u[k] = u[k-1] + \dfrac{K_p}{T_I} e[k]$

$$\Rightarrow \quad D(z) = \frac{K}{T_I} \left(\frac{1}{1 - z^{-1}} \right) = k_I \frac{z}{z-1}$$

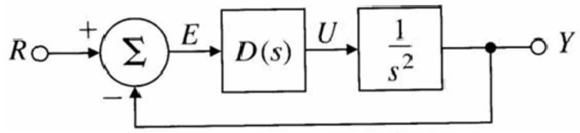
  - Lead Compensation:

$$u[k+1] = \beta u[k] + K \left[e[k+1] - \alpha e[k] \right]$$

$$\Rightarrow \quad D(z) = K \frac{1 - \alpha z^{-1}}{1 - \beta z^{-1}}$$

Franklin et al. 2002

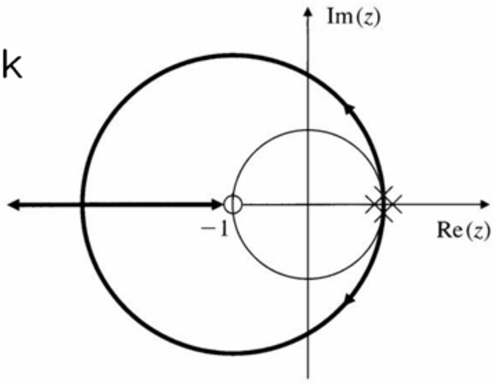
- Space Station Digital Controller example:



$h = 1$

$$G(z) = \frac{h^2}{2}\left[\frac{z+1}{(z-1)^2}\right] = \frac{1}{2}\left[\frac{z+1}{(z-1)^2}\right]$$

with proportional feedback



Franklin et al. 2002

- Space Station Digital Controller example:
  - P + D feedback

$$\Rightarrow \quad U(z) = K\left[1 + T_D\left(1 - z^{-1}\right)\right] E(z)$$

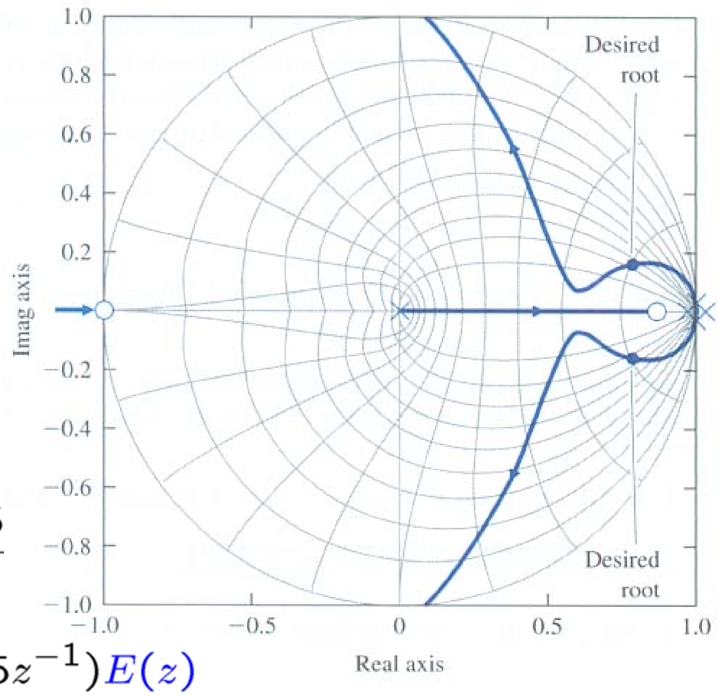
$$\Rightarrow \quad D(z) = K\frac{z-\alpha}{z}$$

$$w_n \approx 0.3 \text{ rad/sec}$$
$$\zeta = 0.7$$
$$\Rightarrow \quad z = 0.78 \pm 0.18\,j$$

Franklin et al. 2002

Discrete Design – Transfer Function

- Space Station Digital Controller example:
  - P + D feedback



$$\Rightarrow \quad D(z) = 0.374 \frac{z - 0.85}{z}$$

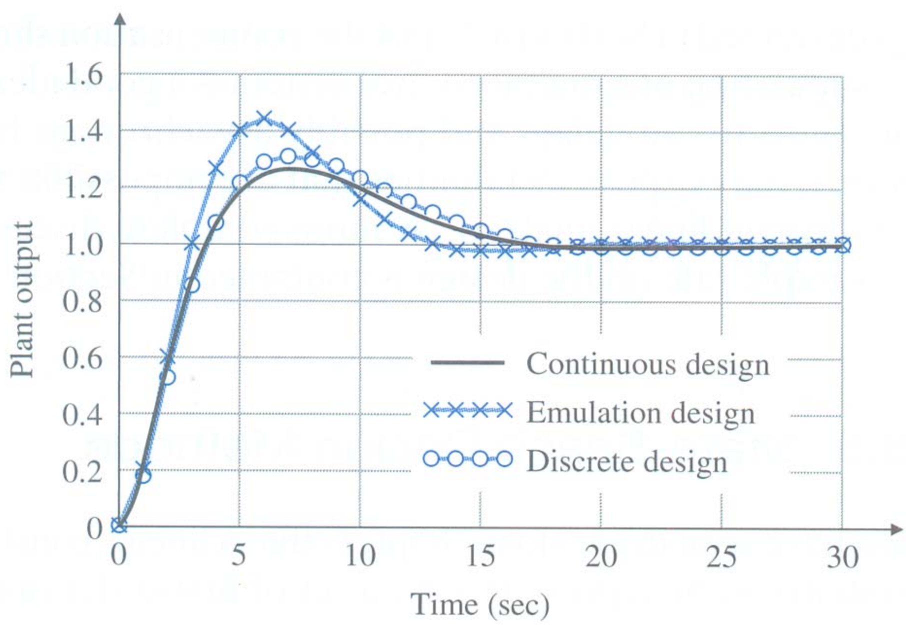
$$\Rightarrow \quad U(z) = 0.374(1 - 0.85z^{-1})E(z)$$

$$\Rightarrow \quad u[k+1] = 0.374e[k+1] - 0.318e[k]$$

Franklin et al. 2002

Discrete Design – Transfer Function

- Step Response of the continuous & digital systems:



ζ	w_n
0.705	0.324
0.645	0.441
0.733	0.306

Franklin et al. 2002

Discrete Design – State Space

- State-Space Model:

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t)\\ y(t) &= \mathbf{C}\mathbf{x}(t) + Du(t)\end{aligned}$$

$$\Rightarrow \ \mathbf{x}(t) = e^{\mathbf{A}(t-t_0)}\mathbf{x}(t_0) + \int_{t_0}^{t} e^{\mathbf{A}(t-\tau)}\mathbf{B}u(\tau)d\tau$$

Let $t = kh + h$ & $t_0 = kh$

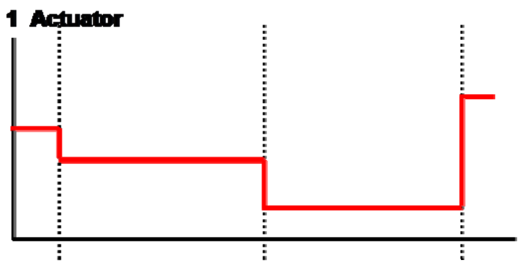
$$\Rightarrow \ \mathbf{x}(kh+h) = e^{\mathbf{A}(h)}\mathbf{x}(kh) + \int_{kh}^{kh+h} e^{\mathbf{A}(kh+h-\tau)}\mathbf{B}u(\tau)d\tau$$

Franklin et al. 2002

Discrete Design – State Space

- State-Space Model:

Let $u(\tau)$ be piecewise constant through h



$$u(\tau) = u(kh), \quad kh \le \tau < kh + h$$

Let $\eta = kh + h - \tau$

$$\Rightarrow \ \mathbf{x}(kh+h) = e^{\mathbf{A}h}\mathbf{x}(kh) + \left(\int_0^h e^{\mathbf{A}\eta}d\eta\right)\mathbf{B}u(kh)$$

Let $\mathbf{F} = e^{\mathbf{A}h}$ & $\mathbf{H} = \left(\int_0^h e^{\mathbf{A}\eta}d\eta\right)\mathbf{B}$

Then,
$$\begin{aligned}\mathbf{x}[k+1] &= \mathbf{F}\mathbf{x}[k] + \mathbf{H}u[k]\\ y[k] &= \mathbf{C}\mathbf{x}[k] + Du[k]\end{aligned}$$

Franklin et al. 2002

- Discrete Transfer Function:

$$\begin{aligned} \mathbf{x}[k+1] &= \mathbf{F}\mathbf{x}[k] + \mathbf{H}u[k] \\ y[k] &= \mathbf{C}\mathbf{x}[k] \end{aligned}$$

$$\begin{aligned} z\mathbf{X}(z) &= \mathbf{F}\mathbf{X}(z) + \mathbf{H}U(z) \\ Y(z) &= \mathbf{C}\mathbf{X}(z) \end{aligned}$$

$$\left(z\mathbf{I} - \mathbf{F}\right)\mathbf{X}(z) = \mathbf{H}\,U(z)$$

$$\Rightarrow \frac{Y(z)}{U(z)} = G(z) = \mathbf{C}\left(z\mathbf{I} - \mathbf{F}\right)^{-1}\mathbf{H}$$

Franklin et al. 2002

- Discrete SS Model of 1/s^2:

$$\begin{aligned} \dot{\mathbf{x}} &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\mathbf{x} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}u \\ y &= \begin{bmatrix} 1 & 0 \end{bmatrix}\mathbf{x} \end{aligned}$$

$$\begin{aligned} \mathbf{F} &= e^{\mathbf{A}h} = \mathbf{I} + \mathbf{A}h + \frac{\mathbf{A}^2h^2}{2!} + \cdots \\ &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}h + \frac{\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}^2 h^2}{2!} + \cdots \\ &= \begin{bmatrix} 1 & h \\ 0 & 1 \end{bmatrix} \end{aligned}$$

Franklin et al. 2002

- Discrete SS Model of 1/s^2:

$$\mathbf{H} = \left(\int_0^h e^{\mathbf{A}\eta} d\eta\right)\mathbf{B} = \sum_{k=0}^{\infty} \frac{\mathbf{A}^k h^{k+1}}{(k+1)!}\mathbf{B}$$

$$= \left(\mathbf{I} + \mathbf{A}\frac{h}{2!}\right) h\mathbf{B}$$

$$= \left(\begin{bmatrix} h & 0 \\ 0 & h \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \frac{h^2}{2}\right) \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} h^2/2 \\ h \end{bmatrix}$$

$$\Rightarrow G(z) = \frac{Y(z)}{U(z)} = \mathbf{C}\left(z\mathbf{I} - \mathbf{F}\right)^{-1}\mathbf{H} = \frac{h^2}{2}\left[\frac{z+1}{(z-1)^2}\right]$$

Franklin et al. 2002

- Pole Placement by State Feedback:

$$\alpha(z) = \det\left(z\mathbf{I} - \mathbf{F}\right)$$

If the system is controllable

$$\mathcal{C} = \begin{bmatrix} \mathbf{H} & \mathbf{F}\mathbf{H} & \mathbf{F}^2\mathbf{H} & \cdots & \mathbf{F}^{n-1}\mathbf{H} \end{bmatrix}$$ is full-rank

$$u[k] = -\mathbf{K}\mathbf{x}[k]$$

$$\Rightarrow \det\left(z\mathbf{I} - \mathbf{F} + \mathbf{H}\mathbf{K}\right) = \alpha_c(z)$$

Franklin et al. 2002

- Discrete Full-Order Estimator:

$$\begin{aligned} \mathbf{x}[k+1] &= \mathbf{F}\mathbf{x}[k] + \mathbf{H}u[k] \\ y[k] &= \mathbf{C}\mathbf{x}[k] \end{aligned}$$

$$\bar{\mathbf{x}}[k+1] = \mathbf{F}\bar{\mathbf{x}}[k] + \mathbf{H}u[k] + \mathbf{L}\left[y[k] - \mathbf{C}\bar{\mathbf{x}}[k]\right]$$

$$\tilde{\mathbf{x}}[k+1] = \left(\mathbf{F} - \mathbf{L}\mathbf{C}\right)\tilde{\mathbf{x}}[k] \qquad (\tilde{\mathbf{x}} = \mathbf{x} - \bar{\mathbf{x}})$$

If the system is observable, $\mathcal{O} = \begin{bmatrix} \mathbf{C} \\ \mathbf{C}\mathbf{F} \\ \mathbf{C}\mathbf{F}^2 \\ \vdots \\ \mathbf{C}\mathbf{F}^{n-1} \end{bmatrix}$ is full-rank

$$\Rightarrow \det\left(z\mathbf{I} - \mathbf{F} + \mathbf{L}\mathbf{C}\right) = \alpha_e(z)$$

Franklin et al. 2002

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