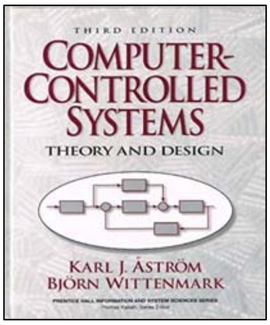
Spring 2019

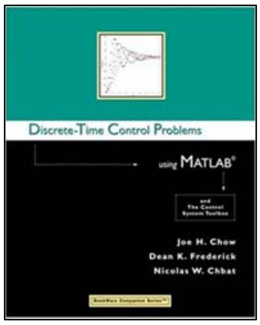
數位控制系統
Digital Control Systems

DCS-01
Computer Control



Feng-Li Lian
NTU-EE

Feb19 – Jun19

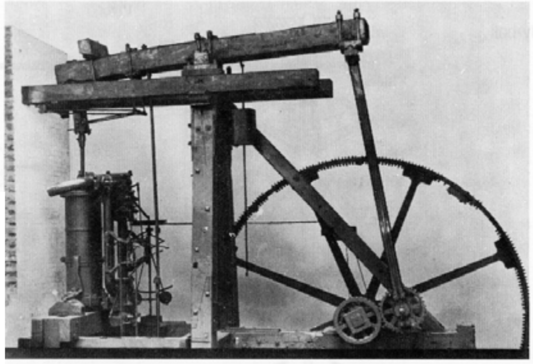


Syllabus

- Lecture Information:
  - Time: Fridays 1:40pm-4:30pm
  - Room: MD-225
  - Office Hours: by e-mail appointment
  - Website: http://cc.ee.ntu.edu.tw/~fengli/Teaching/DigitalControl
- Instructor:
  - 連豊力(Feng-Li Lian)
  - Office: MD-717
  - Email: fengli@ntu.edu.tw
  - Phone: 02-3366-3606
- Grading:
  - Homework (30%) bi-week
  - Midterm (30%) on x/y
  - Project (40%) on x/y
- Textbook:
  - Computer-Controlled Systems: Theory & Design, 3rd. Ed., (1997), by Astrom & Wittenmark
  - Discrete Time Control Problems Using Matlab and the Control System Toolbox, (2003), by Chow, Frederick & Chbat
- References:
  - Digital Control of Dynamic Systems, 3rd Ed., (1998), by Franklin, Powell, Workman
  - Real-Time Systems, (1997), by Krishna & Shin
  - Real-Time Computer Control: An Introduction, 2nd Ed., (1994), by Bennett
  - Control in an Information Rich World, Report of the Panel on Future Directions in Control, Dynamics, and Systems. http://www.cds.caltech.edu/~murray/cdspanel/report/cdspanel-15aug02.pdf

Introduction: Analog Control

Figure 1.9
A steam engine from the shop of James Watt.
(*British Crown Copyright, Science Museum, London*)



Franklin, Powell, Emami-Naeini 2002

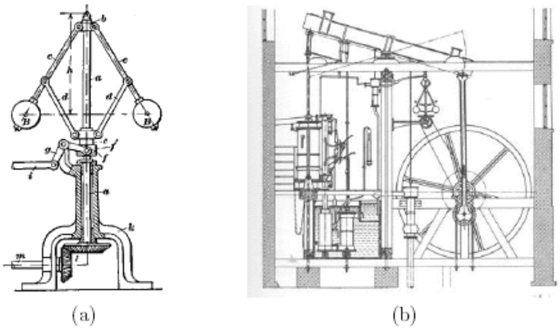
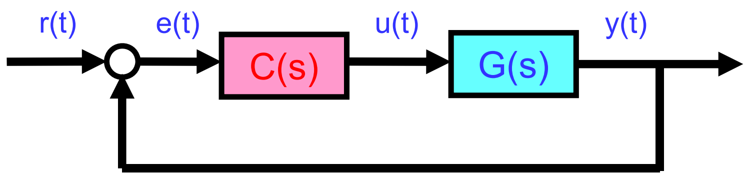


Figure 1.1. *The centrifugal governor (a), developed in the 1780s, was an enabler of the successful Watt steam engine (b), which fueled the industrial revolution. Figures courtesy of Cambridge University.*

Murray 2002



Introduction: Digital Control Systems

Murray 2002

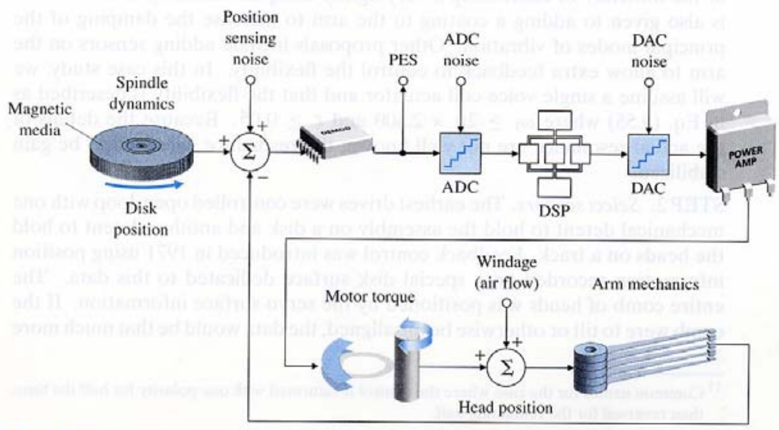
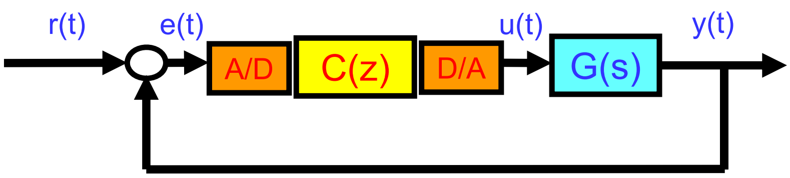
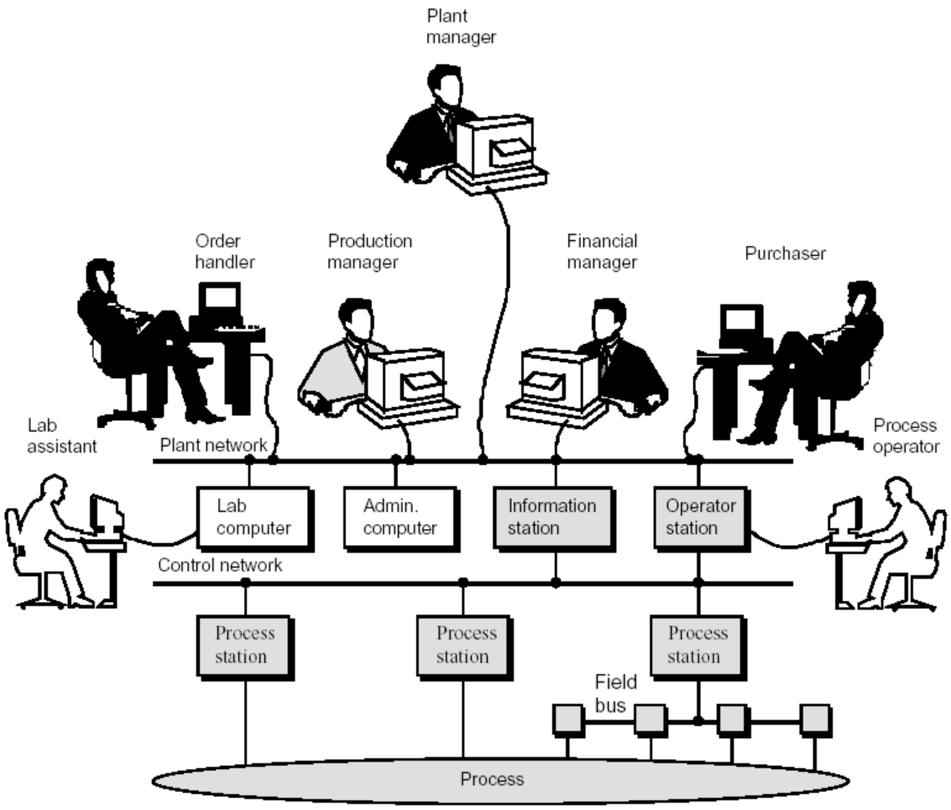


Figure 9.73 Generalized view of track-following model

Franklin, Powell, Emami-Naeini 2002



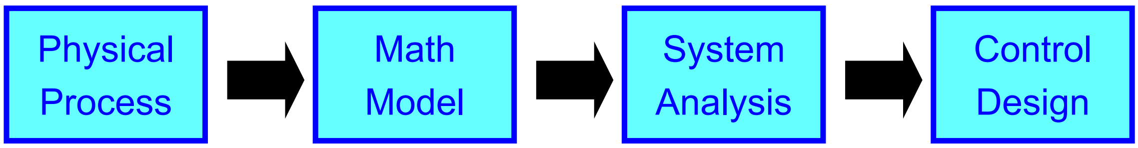
Introduction: Distributed, Networked Control Systems



Astrom & Wittenmark 1997

The Design Philosophy of Control Science

- The Research Procedure in Control Science



- Plant
- Sensor
- Actuator
- Computer
- Communication
- Noise
- Disturbance

- Differential eqn
- Laplace transform
- Transfer function
- State space form

- Difference eqn
- z transform
- Transfer function
- State space form

- Root locus
- Bode diagram
- Nyquist plot

- Stability
- Robustness
- Sensitivity
- Controllability
- Observability

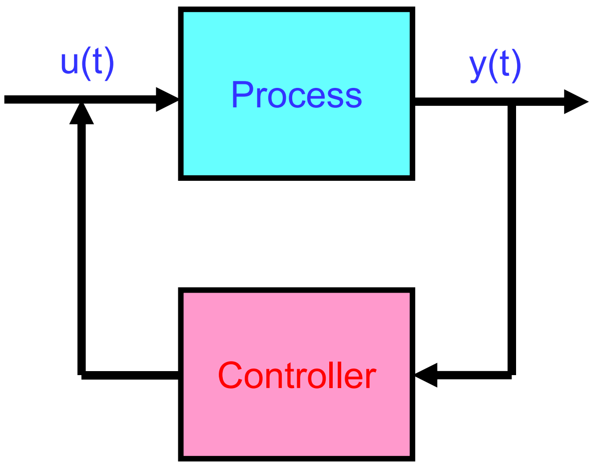
- Estimator
- Identification
- Regulation
- Tracking
- PID
- Pole placement
- Optimal Control LQR/LQG
- Adaptive control
- Robust control
- Decentralized (or Multi-person) Control

Learning Controls for Linear Systems

	Control Systems	Linear Systems	Optimal Control	Adaptive Control	Robust Control	Stochastic Control
Topics	Transfer Function: Input-Output model Root Locus Bode Plot PID Compensator Regulation Tracking/Servoing	State Space: Internal model Eigenvalue Pole/Zero Pole Placement State Feedback State Observer Output Feedback	Optimization Objective Constraint LQR LQG	Parameter Estimation	Gain Upper Bound	Uncertain Distribution

CT **Continuous Time**	**Differential Eqn** **Laplace Transform** **Polynomial of s**	**Differential Eqn** **Matrix**
DT **Discrete Time**	**Difference Eqn** **z-Transform** **Polynomial of z**	**Difference Eqn** **Matrix**

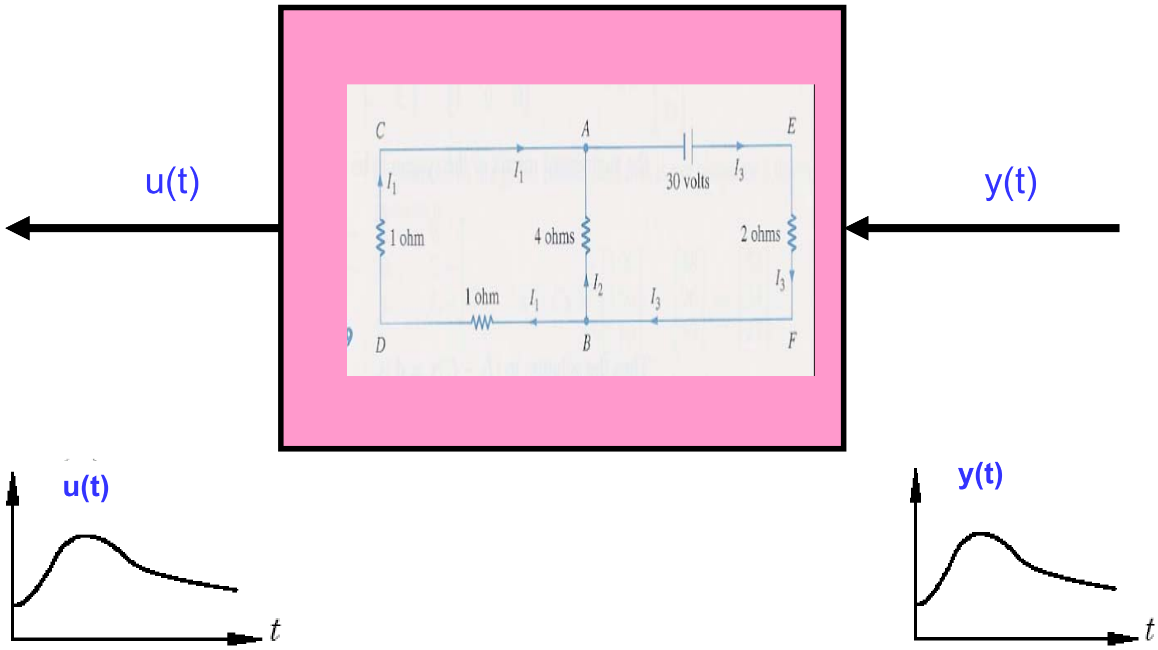
Feedback Control Systems



- Analog Controller:
- Digital Controller:

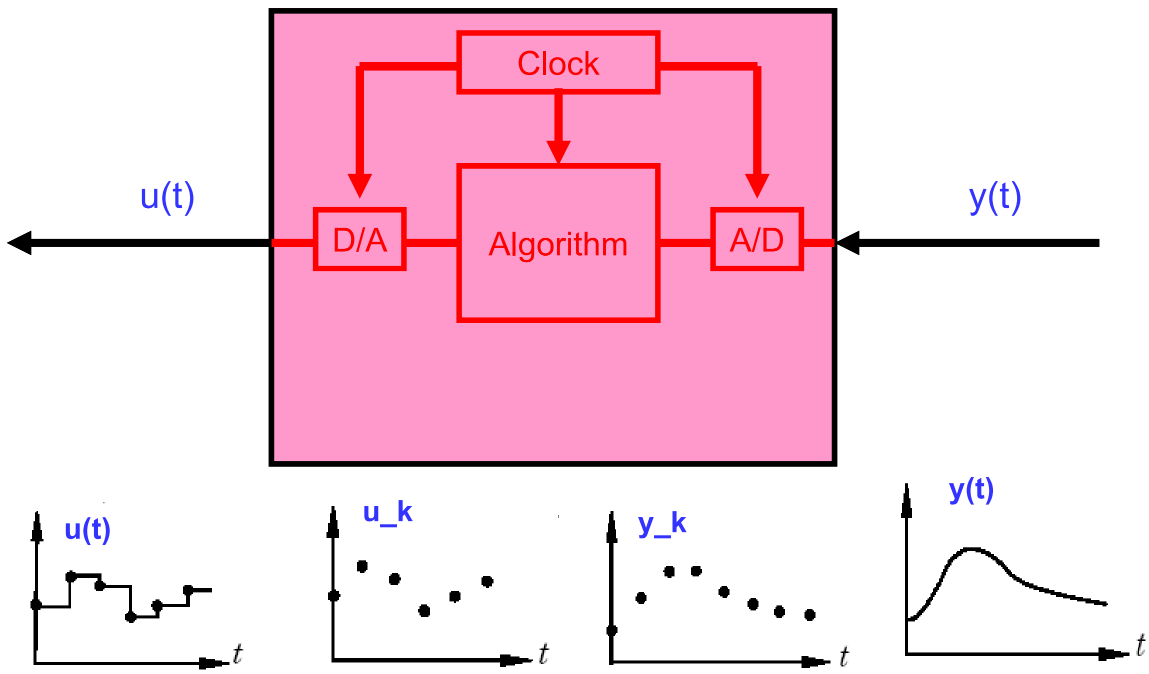
Introduction: Analog Controller

- Analog Controller:



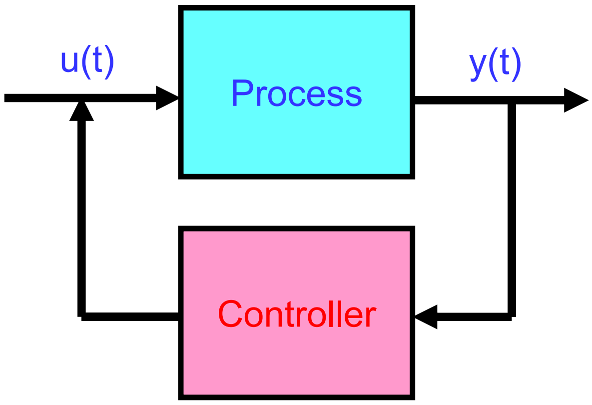
Introduction: Digital Controller

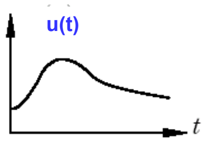
- Digital Controller:



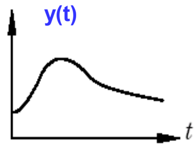
Introduction: Control Systems

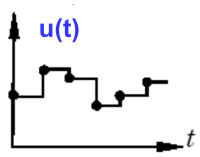
- Control Systems:



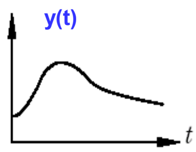


- Analog Controller:

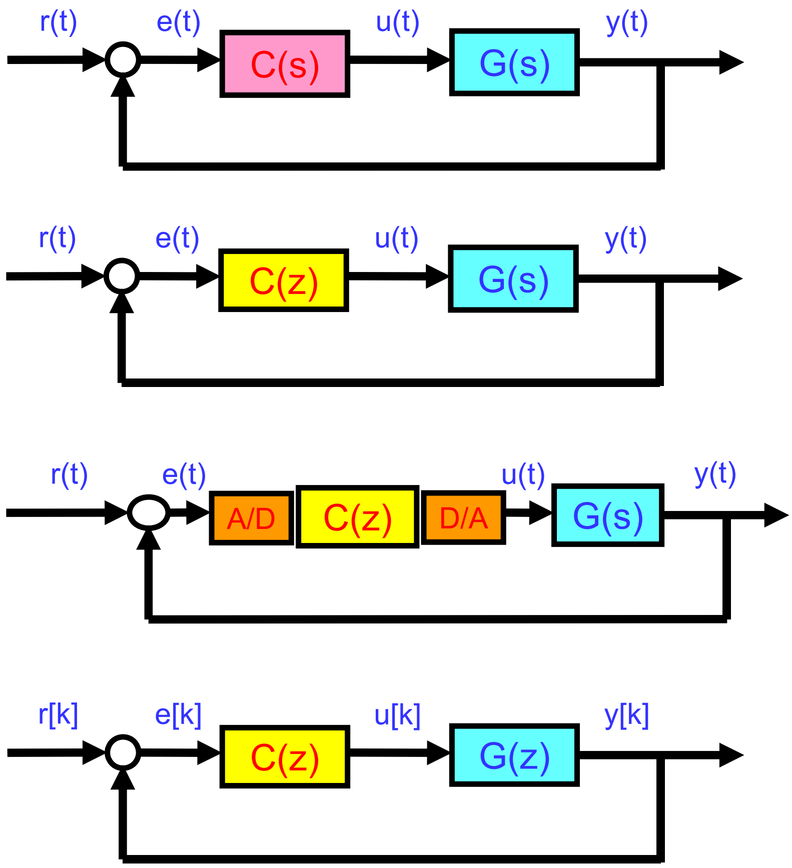


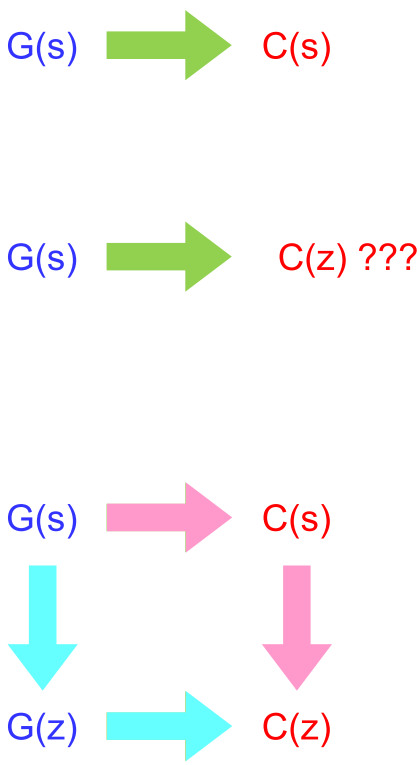


- Digital Controller:

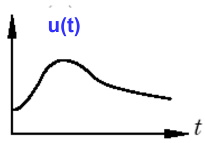


Introduction: Analog Control and Digital Control

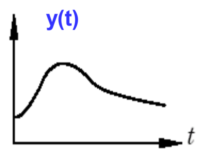


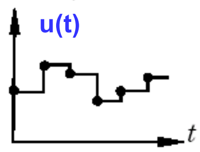


Introduction: Analog and Digital Controllers

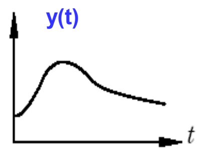


- Analog Controller:
- Continuous-time systems





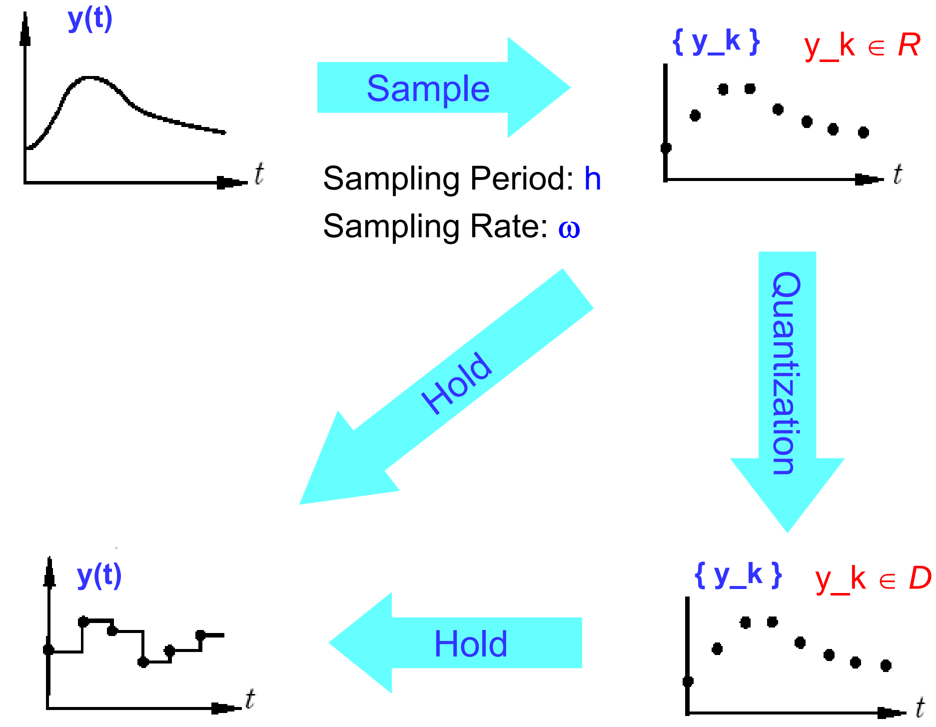
- Digital Controller:
- Discrete-time systems
- Sampled-data systems
- Computer-controlled systems
- Digital control systems



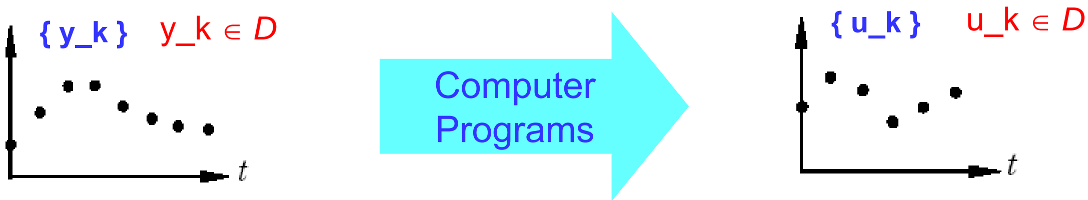
Introduction: Discrete-Time Signals

- Digital Signals
  - D: Resolution set of digital signals
  - e.g., Use 3 bits to represent a signal between –7V to 7V
  - then, 2^3 = 8
    - that is, there are 8 levels and 7 intervals
  - so, [7 – (-7)] / 7 = 2
  - hence,
    - 000 = 0) -7V
    - 001 = 1) -5V
    - 010 = 2) -3V,
    - …
    - 111 = 7) 7V
  - So, D = { -7, -5, …, 7 }
    - which can be mapped into Z+ = {0, 1, 2, …,N}

▪ Discrete-Time Signals



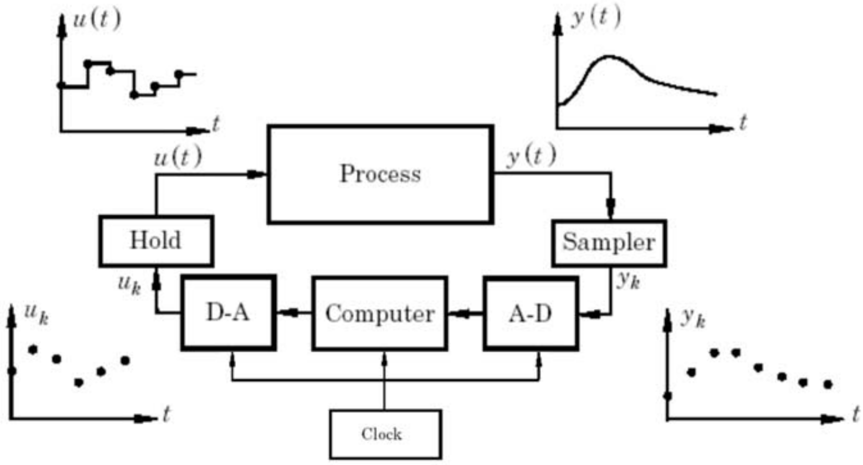
▪ Digital Controller:



controller algorithm

$$\{u_k\} = g(\{y_k\})$$

- Goals of this course:
  - To understand discrete-time systems
  - To understand digital control systems
  - To be able to design digital controllers
  - To understand the problems with implementation
- Main Components of Digital Control Systems

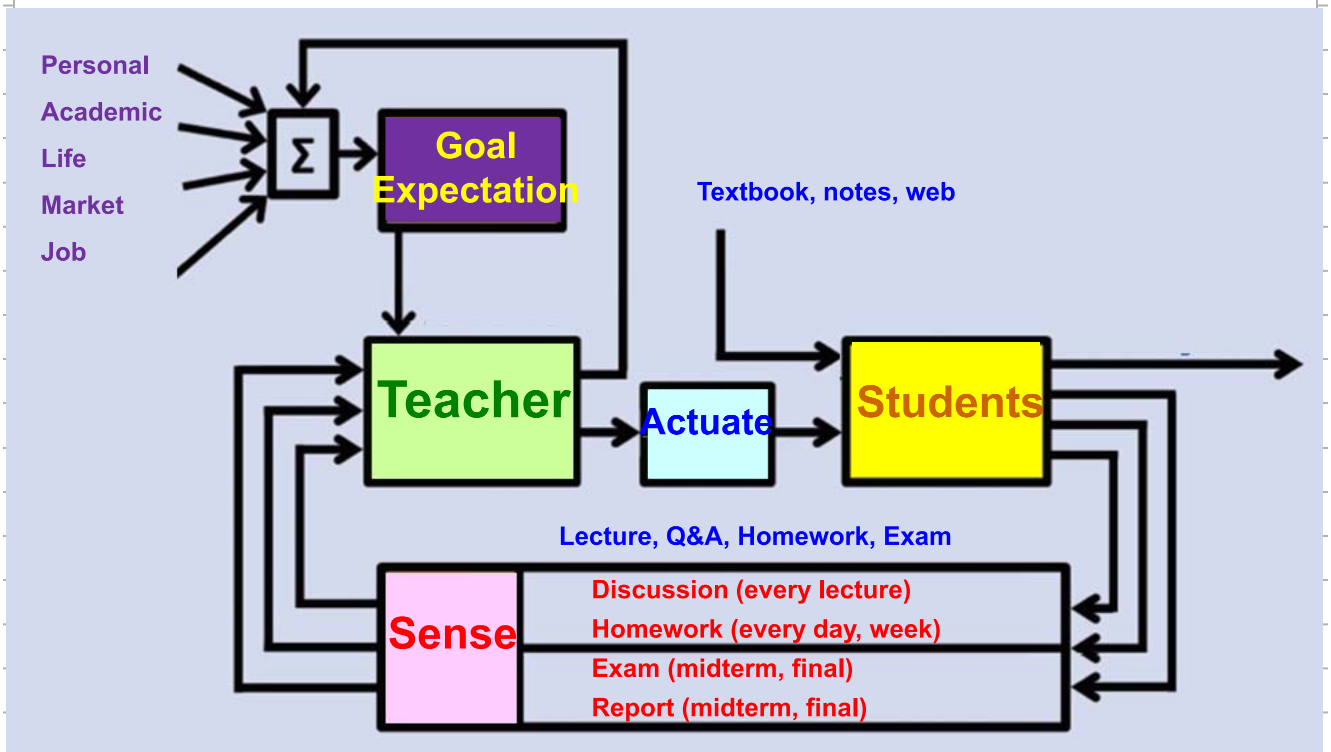


- Inherently Sampled Systems:
  - Sampling due to the Measurement System
    - Radar
      - > Radar antenna rotates & info is naturally obtained once per revolution.
    - Analytical Instruments
      - > Process data are sampled and analyzed off-line.
    - Economic Systems
      - > Accounting data are accumulated daily, weekly, monthly, or yearly.
    - Magnetic Flow Meters
      - > The magnetic field in a typical meter is switched on and off periodically.
  - Sampling due to Pulsed Operation
    - Thyristor Control in Power Electronics
    - Biological Systems
    - Internal-Combustion Engines
    - Particle Accelerators

- Homework Reading 1-A:
  - ✓Astrom & Wittenmark 1997
  - ✓Pages 22-24

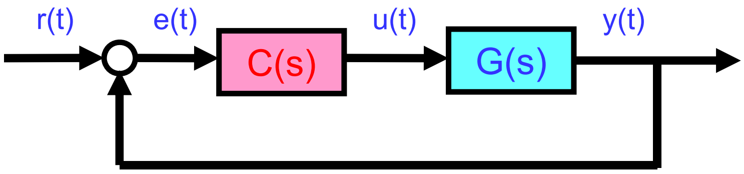
- Key **Features** of Digital Control Systems:
  - Time-varying and time dependence
  - A naïve approach by approximation
  - Deadbeat control
  - Aliasing and anti-aliasing filters
  - Differential equations & difference equations

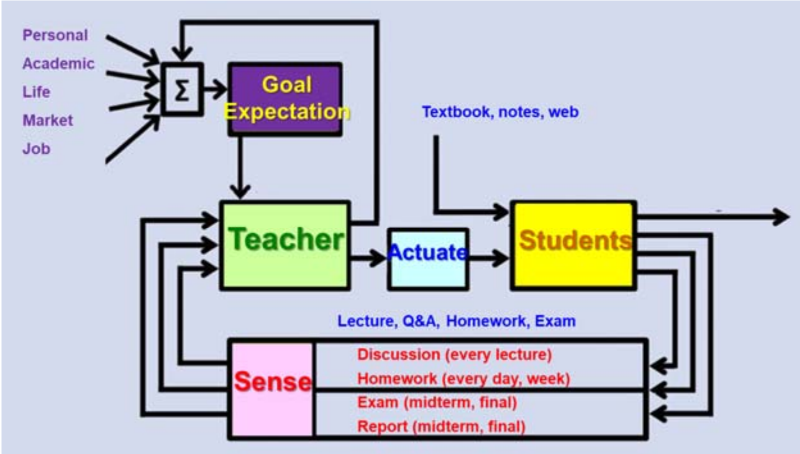
- Key **Variables** in Digital Control Systems:
  - Sampling — h
  - Time Delay — $\tau : \tau < h$ or $\tau = m\, h$
  - Quantization — $x : x \in R$ or $x \in D$



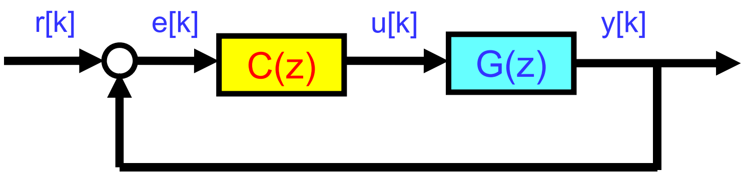
Source：IEEE CSM 2013

Introduction: Learning Control



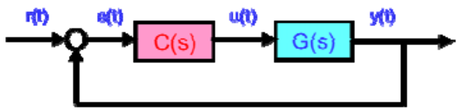


- Sampling
- Time Delay
- Quantization

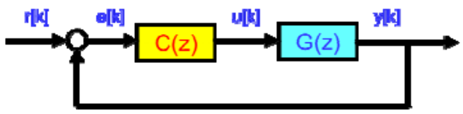


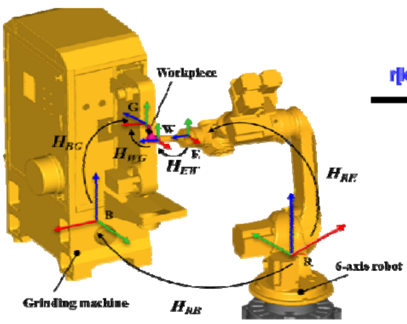
Source：IEEE CSM 2013

Introduction: Cyber-Physic System, VR, AR



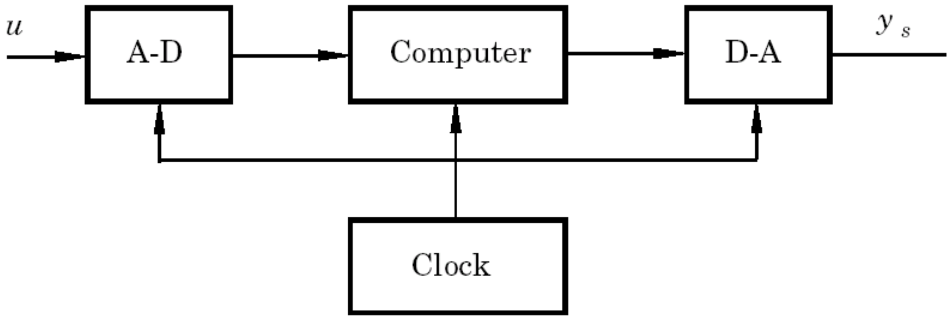
- Sampling
- Time Delay
- Quantization

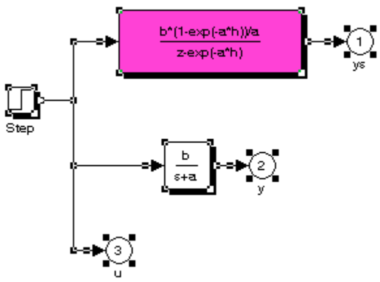


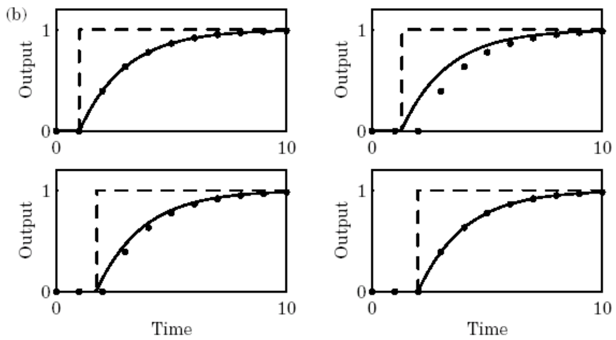


Source：ITRI, Robotics,
https://asia.playstation.com/cht-tw/psvr/features/,
http://geographical.co.uk/nature/geophoto/item/2291-under-the-sea

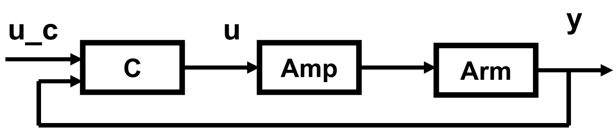
- Example: Time dependence in digital filtering







- Example: Controlling the arm of a disk drive



Control of the arm of a disk drive

$$G(s) = \frac{k}{Js^2}$$

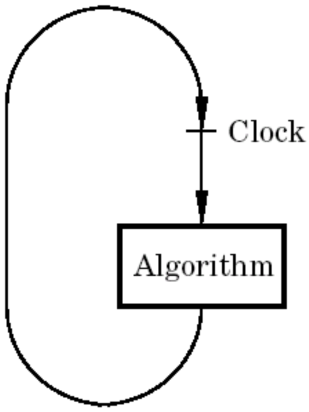
Continuous time controller

$$U(s) = \frac{bK}{a} U_c(s) - K \frac{s+b}{s+a} Y(s)$$

Discrete time controller

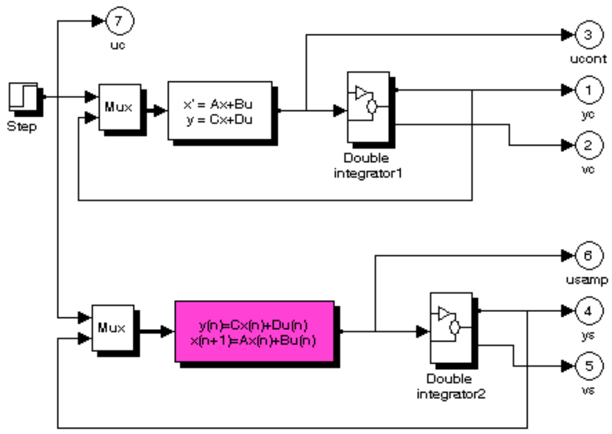
$$u(t_k) = K\left(\frac{b}{a} u_c(t_k) - y(t_k) + x(t_k)\right)$$
$$x(t_k + h) = x(t_k) + h\left((a-b)y(t_k) - ax(t_k)\right)$$

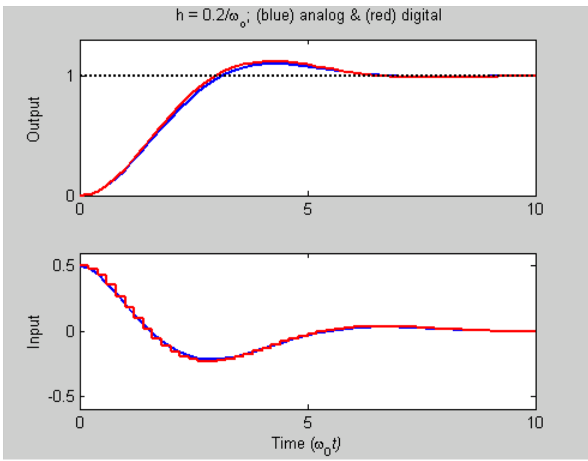
- Example: Controlling the arm of a disk drive




```
y: = adin(in2) {read process value}
u:=K*(a/b*uc-y+x)
dout(u)  {output control signal}
newx:=x+h*((b-a)*y-b*x)
```


- Example: Controlling the arm of a disk drive

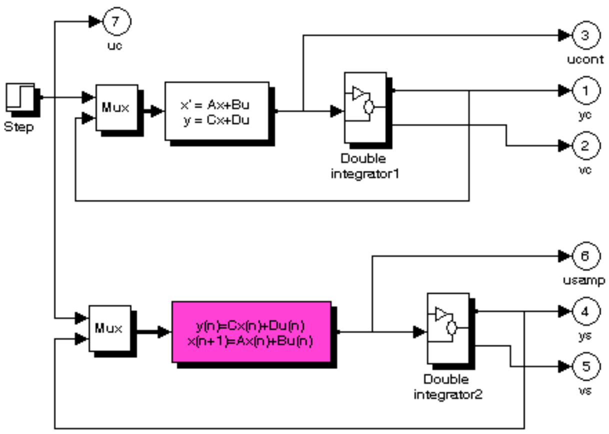


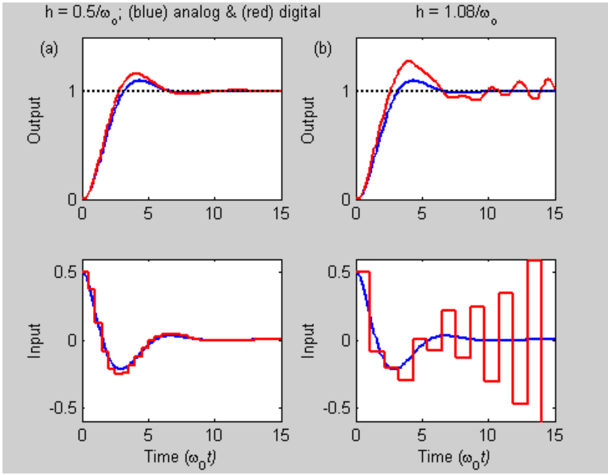


- Example: Controlling the arm of a disk drive

Increased sampling period

a) $h = 0.5/\omega_0$ b) $h = 1.08/\omega_0$



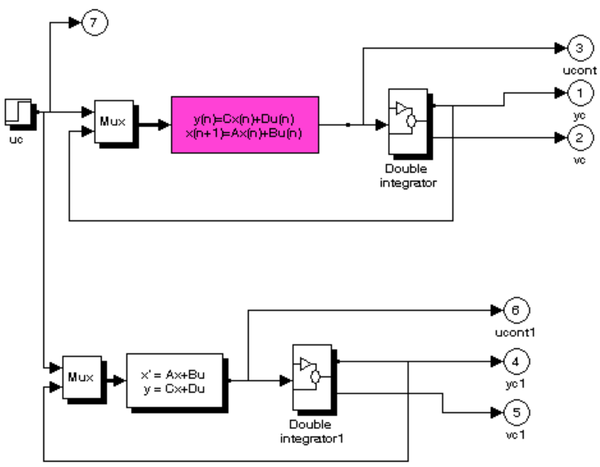


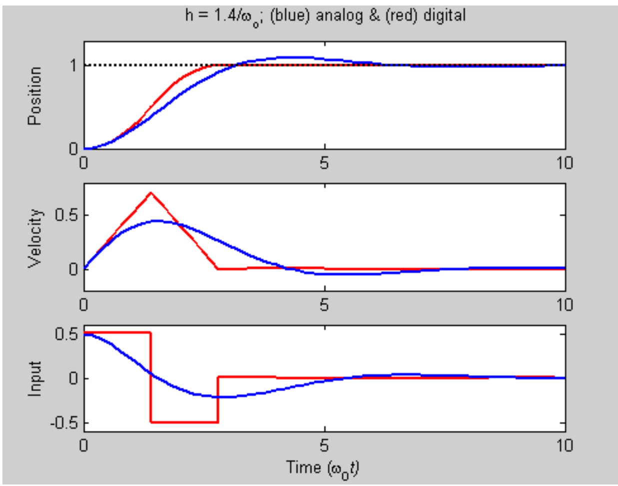
- Example: Disk drive with deadbeat control

Better performance?

Dead-beat control $h = 1.4/\omega_0$

$$u(t_k) = t_0 u_c(t_k) + t_1 u_c(t_{k-1}) - s_0 y(t_k) - s_1 y(t_{k-1}) \\ - r_1 u(t_{k-1})$$





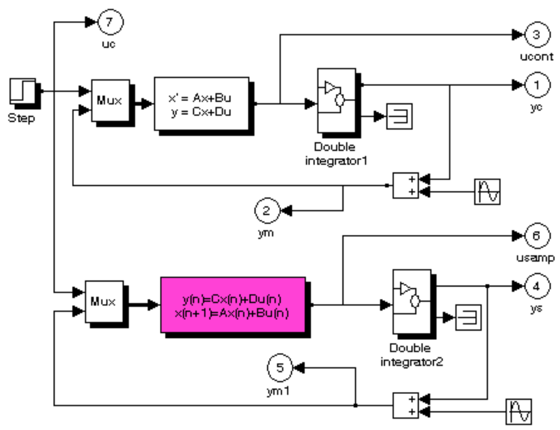
▪ Example: Sampling creates new frequencies

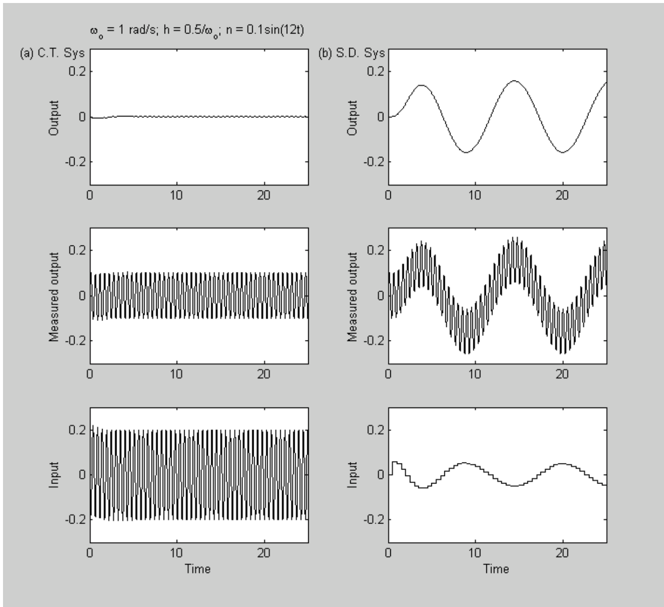
Sinusoidal measurement noise

Double integrator with $\omega_0 = 1$ and $h = 0.5$
Measurement noise $0.1 \sin 12t$
a) Continuous time, b) Discrete time

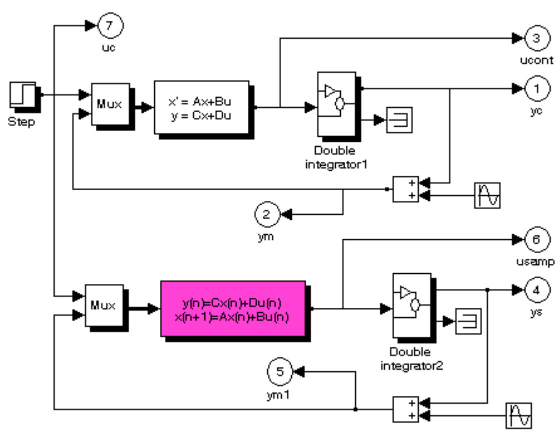
$$\omega_{sampled} = |\omega \pm n\omega_s|$$

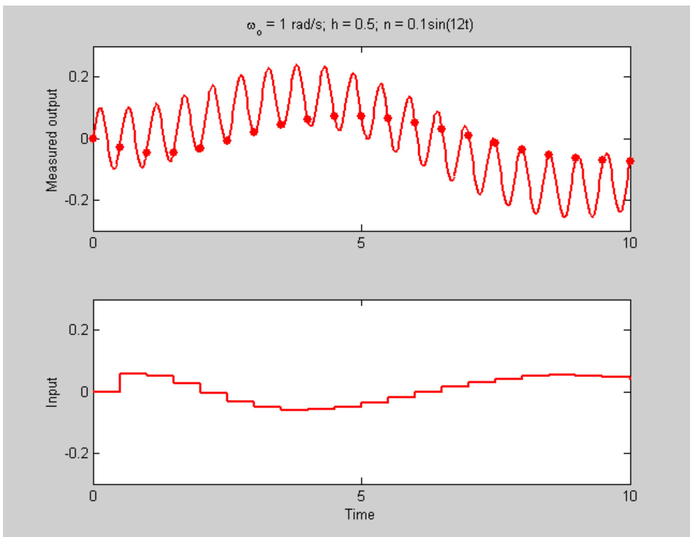
Sampling frequency $\omega_s = 2\pi/h$





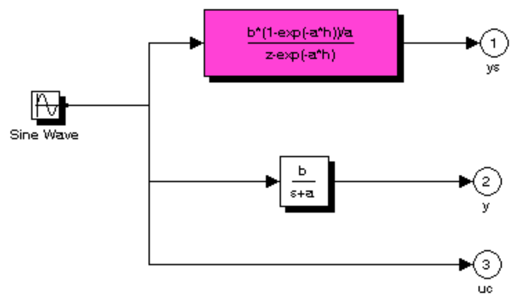
▪ Example: Sampling creates new frequencies

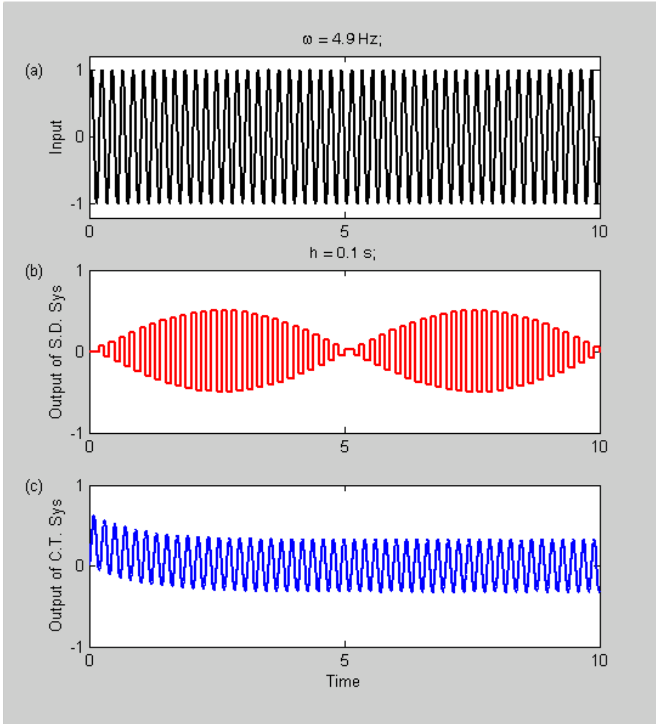




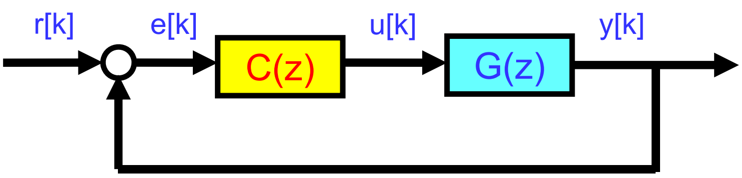
The sampling period is too long compared with the noise
Important to filter before sampling!

- Example: Creation of higher frequencies by sampling





- Example: Difference Equations



$$G(z) = \frac{Y(z)}{U(z)} = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

$$y[k] + a_1 y[k-1] + a_2 y[k-2]$$

$$= b_0 u[k] + b_1 u[k-1] + b_2 u[k-2]$$

Introduction: Fundamental Theories

- Theories needed:
  - Sampling Theorem
  - Difference Equations
  - Numerical Analysis
  - Transform Methods
  - Algebraic System Theory
  - State-Space Theory
  - Optimal & Stochastic Control
  - System Identification
  - Adaptive Control

- Homework Reading 1-B:
  - ✓Astrom & Wittenmark 1997
  - ✓Pages 25-28

Introduction: Historical Notes and References

1.6 Notes and References

To acquire mature knowledge about a field it is useful to know its history and to read some of the original papers. Jury and Tsypkin (1971), and Jury (1980), written by two of the originators of sampled-data theory, give a useful perspective. Early work on sampled systems is found in MacColl (1945), Hurewicz (1947), and Oldenburg and Sartorius (1948). The sampling theorem was given in Kotelnikov (1933) and Shannon (1949).

Major contributions to the early theory of sampled-data systems were obtained in England by Lawden (1951) and Barker (1952); in the United States by Linvill (1951), Ragazzini and Zadeh (1952), and Jury (1956); and in the Soviet Union by Tsypkin (1949) and Tsypkin (1950).The first textbooks on sampled-data theory appeared toward the end of the 1950s. They were Jury (1958), Ragazzini and Franklin (1958), Tsypkin (1958), and Tou (1959). A large number of textbooks have appeared since then. Among the more common ones we can mention Ackermann (1972, 1996), Kuo (1980), Franklin and Powell (1989), and Isermann (1989, 1991).

The idea of formulating control problems in the state space also resulted in a reformulation of sampled-data theory. Kalman (1961) is seminal.

Some fundamental references on optimal and stochastic control are Bellman (1957), Bellman, Glicksberg, and Gross (1958), Kalman (1960a), Pontryagin et al. (1962), and Åström (1970). The algebraic system approach is discussed in Kalman, Falb, and Arbib (1969), Rosenbrock (1970), Wonham (1974), Kučera (1979, 1991, 1993), and Blomberg and Ylinen (1983).

System identification is surveyed in Åström and Eykhoff (1971), Ljung and Söderström (1983), Norton (1986), Ljung (1987), Söderström and Stoica (1989), and Johansson (1993). Adaptive control is discussed in Bellman (1961), Åström and Wittenmark (1973, 1980, 1995), Åström (1983b, 1987), Goodwin and Sin (1984), Gupta (1986), and Åström and Hägglund (1995).

A survey of distributed computer systems is found in Lucas (1986). In Gustafsson, Lundh, and Söderlind (1988), it is shown how step-length control in numerical integration can be regarded as a control problem. This is also discussed in Hairer and Wanner (1991).

Many additional references are given in the following sections. We also recommend the proceedings of the IFAC Symposia on Digital Computer Applications to Process Control and on Identification and System Parameter Estimation, which are published by Pergamon Press.

- Homework Reading 1-D:
  - ✓Astrom & Wittenmark 1997
  - ✓Pages 28-29

Introduction: Computer Technology for Control

- Pioneering Period ≈ 1955
  - TRW, Texaco
  - 26 flows, 72 temperatures, 3 pressures, 3 compositions
  - (+, x, MTBF) = (1 ms, 20 ms, 50-100 h)
- Direct-Digital-Control Period ≈ 1962
  - ICI
  - 224 variables, 129 valves
  - (+, x, MTBF) = (100 μs, 1 ms, 1,000 h)
- Mini-Computer Period ≈ 1967
  - (+, x, MTBF, #, $) = (2 μs, 7 μ s, 20,000 h, 5,000, $100,000)
- Micro-Computer Period ≈ 1972
  - (+, x, MTBF, #, $) = ($10,000)
- General Use of Digital Control Period ≈ 1980
  - VLSI, AD-DA
  - (+, x, MTBF, #, $) = ($500)
- Distributed Control Period ≈ 1990

- Homework Reading 1-C:
  - ✓Astrom & Wittenmark 1997
  - ✓Pages 2-11

Introduction: Course Outline

- Digital Control Systems
  - From Analog to Digital World
  - Design Consideration
  - Z-transform
  - Controller Design
- Computer Control Systems (Single Centralized Control)
  - Real-Time Operation Systems
  - Analog to Digital
  - Digital to Analog
- Networked Control Systems (Multiple Distributed Control)
  - Control Networks Protocols
  - Networked Controllers & Managers
  - Networked Sensors
  - Networked Actuators

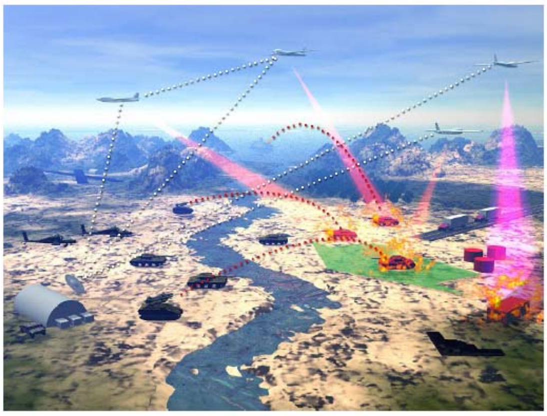
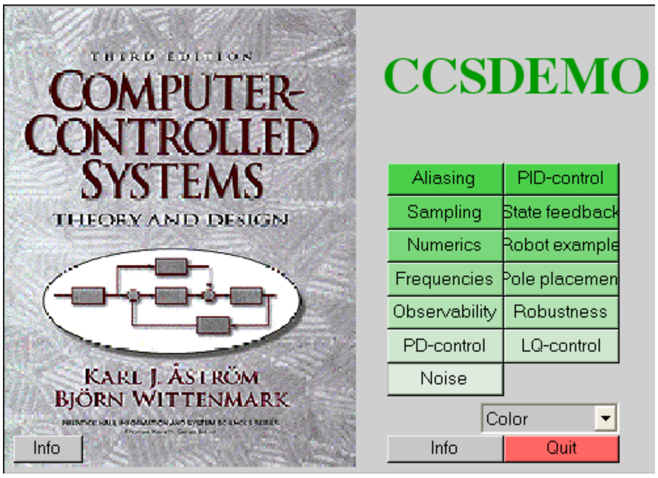
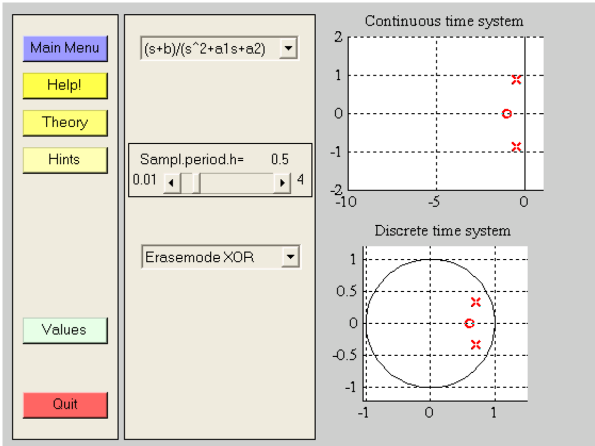


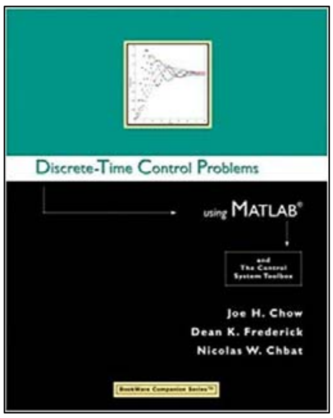
Figure 3.2. *Battle space management scenario illustrating distributed command and control between heterogeneous air and ground assets. Figure courtesy of DARPA.*

- CCSDEMO by Astrom & Wittnemark of Lund





- Discrete Time Control Problems
  Using Matlab and the Control System Toolbox, (2003)
  - by Joe H. Chow, Dean K. Frederick, Nicholas W. Chbat
- Table of Content:
  - 1. INTRODUCTION
  - 2. SINGLE-BLOCK MODELS AND THEIR RESPONSES
  - 3. BUILDING AND ANALYZING MULTI-BLOCK MODELS
  - 4. STATE-SPACE MODELS
  - 5. SAMPLE-DATA CONTROL SYSTEMS
  - 6. FREQUENCY RESPONSE, DIGITAL FILTERS, AND DISCRETE EQUIVALENTS
  - 7. SYSTEM PERFORMANCE
  - 8. PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROL.\
  - 9. FREQUENCY-RESPONSE DESIGN
  - 10. STATE-SPACE DESIGN METHODS
  - A: Models Of Practical Systems.
    Ball and Beam System.
    Inverted Pendulum.
    Electric Power System.
    Hydro-Turbine and Penstock.
  - B: Root-Locus Plots. Discrete Fourier Transform.
  - C: Matlab Commands.

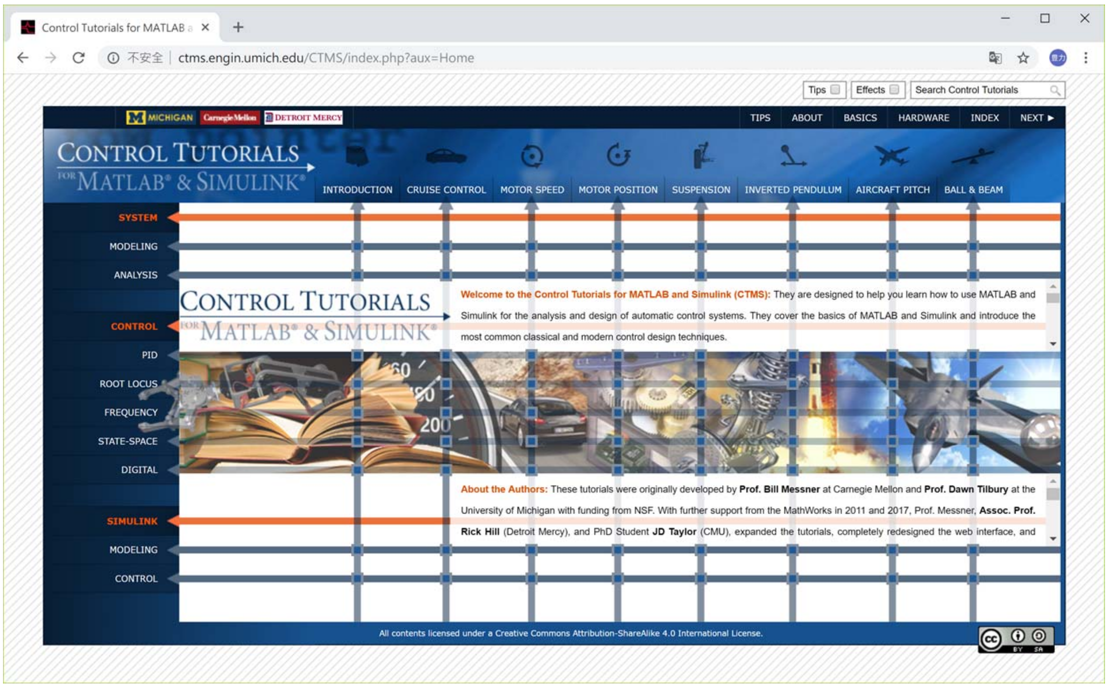


Introduction: Computer Aided Tools

- Control Tutorial for Matlab & Simulink

  by Tilbury of UMich & Messner of CMU

  http://ctms.engin.umich.edu/CTMS/



Grading: Homework (30%)

- Grading:
  - Homework (30%)
  - Midterm (30%)
  - Project (40%)

- About 6 homeworks

- Assigned and to be submitted every two weeks

Grading: Midterm (30%)

- Grading:
  - Homework (30%)
  - Midterm (30%)
  - Project (40%)
- Date:
  - x/y in class from 2pm-4pm
- Cover:
  - Discrete-Time Systems and Signals
  - Analysis of Discrete-Time Systems
  - Controller Design of Discrete-Time Systems
  - The detailed derivation of every equation discussed in class
  - Explaining any simulation plots in textbook
  - Homework assignments
- Closed books, no notes or handouts

Grading: Term Project (40%)

- Team members:
  - About 1-3 students of different levels
  - Auditing/Visiting students are encouraged to join a team
- Subject/Title:
  - Theoretical study
    - Study any digital control theory and derive possible new results
  - Simulation study
    - Detailed and thorough simulation study of one application
  - Software package development of digital control systems
    - Develop toolkits similar to CCSDemo and Control Tutorial
- Agenda:
  - x/y: Form a team and submit one-page proposal
  - x/y: Progress Report
  - x/y: Presentation & Final Report

Grading: Term Project (40%)

- "Economy" Class:
  - Only 1 student
  - Simulation study of one typical control application
    - Such as flight, DVD/HD, motor, robot, etc.
    - Should include modeling, (timing) analysis, design, and simulation validation
- "Business" Class:
  - >= 2 students
  - >= 10 digital-control-related IEEE journal papers
  - Could only focus on one or two of the following areas:
    - Modeling, (system or timing) analysis, design, etc.
  - Strongly suggest to re-do the simulation results in the survey papers
- "First" Class:
  - <= 3 students
  - >= 20 digital-control-related IEEE journal papers
  - Generate good/nice (possibly new) theoretical results
  - Develop different (possibly useful) digital-control-related software package

Grading: Term Project (40%)

- Agenda:
  - x/y: Submit one-page proposal
    - > Including title, team members, affiliation, etc.,
      and one or two paragraphs describing your ideas
  - x/y: Progress Report
    - > Less than 5 pages including preliminary results and current status
  - x/y: Presentation
    - > In PowerPoint format if possible
  - x/y: Final Report
    - > One zipped file of the related electronic files
      including documentation and presentation files, etc.
      - » Please e-mail the link to the files of the report to fengli@ntu.edu.tw
        Deadline: By 11pm, day, x/y

- Grading (40%):
  - Report (30% from group performance):
    - Writing style & contents (10%)
      - Title
        - Does "title" actually and precisely reflect the content of this report?
      - Introduction
        - Does it provide enough background information about this study?
        - Are references properly cited?
      - Main results, including theoretical derivation or simulation study
        - Do it explicitly and concisely describe the results?
        - Are they good or solid enough to give readers any useful information?
      - Discussions, summary/conclusions
        - Does it conclude anything and provide good suggestion for the future?
      - References
        - Does it list enough cited papers?
    - Technical content (20%)
      - The contents on main result and discussions

- Grading (40%):
  - Presentation (10% from individual performance):
    - Evaluation by instructor (5%)
    - Evaluation by other students (5%)
    - Suggested Format:
      - Each group should use PowerPoint to give a formal presentation.
      - Every group member should provide at least 7-min talk.
      - After everyone's presentation, we will have Question-&-Answer session!