Faculty of Engineering
Computer and Systems
Engineering Department

CSE 372: Control Systems (2)

Topic# 1

Introduction to Digital Control Systems

Prof. Wahied Gharieb Ali

CSE 372: Control Systems (2)

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Textbook:

1) M. Sami Fadali and Antonio Visioli, "**Digital Control Engineering**: ***Analysis and Design***", Academic Press (Elsevier) 2nd edition, 2013.
2) Norman S. Nise, "**Control Systems Engineering**", Chapter 13, John Wiley & Sons, 6th edition, 2011.
3) Edited by William S. Levine, "**Control Systems Fundamentals**", CRC Press Taylor & Francis Group, Section IV – ***Digital Control***, 2011.
4) Ioan D. Landau and Gianluca Zito, "**Digital Control Systems**: ***Design, identification, and Implementation***", Springer-Verlag 2006.

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Additional Readings:

5) Wikibooks, "**Control Systems**", free download from **http://en.wikibooks.org/wiki/Control_Systems** , 2013.
6) Farid Golnaraghi and benjamin C. Kuo, "**Automatic Control Systems**", 9th Edition, John Wily & Sons, 2010.
7) K. J. Astrom and B. Wittenmark, "**Computer Controlled Systems**", Prentice Hall, 3rd Edition, 1997.
8) K. Ogata, "**Discrete Time Control Systems**", Prentice Hall, 2nd Edition 1995.
9) C. A. Rabbath and N. Léchevin, "**Discrete-Time Control System Design with Applications**", Springer 2014.
10) Gregory P. Starr, "**Introduction to Applied Digital Control**", Department of Mechanical Engineering The University of New Mexico, technical notes, 2nd edition, 2006.

Course Grading	**Quizzes (10)**	**Assignments (10)**
	Tutorial (10)	**Micro Project (10)**
	Final Exam (110)	

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Course Policies:

1. Homework Submission:
   Homework solutions should be submitted on the due date.
2. Late homework policy:
   On time, in the class (100%), same day after class (90%), next day (70%), 2 days (50%), 3 days or more (0%).
3. Collaboration:
   You are encouraged to discuss the assigned problems/projects with your classmates. But you are not allowed to talk about the final solution itself or to show your solution to others. Every student has to prepare his/her solution independently.
4. Preparing the final solution:
   Please write your solution in a clear, readable, and concise form. Every answer should be fully justified.

Course Objectives

- Provide a background of digital control engineering and its applications.
- Analysis & design of digital control systems using transform and state-space techniques.
- Study the fundamentals of real time programmable controllers and SCADA systems.
- Emphasize the use of MATLAB for analysis and design.

Course Outline

- Introduction to Control Systems
- Sampled data systems and Z-transform
- Sampling and reconstruction
- Pulse transfer function
- Control design methods
- State space analysis and design
- Real time practical considerations
- Embedded Control systems
- Programmable Logic Controllers (PLCs)
- Supervisory control and SCADA Systems
- Course recap

Introduction to Control Systems

1. **Linear Systems**
2. **Digital Control**
3. **Nonlinear Systems**
4. **Adaptive Control**
5. **Robust Control**
6. **Optimal Control**
7. **Intelligent Control**

Introduction to Control Systems

Control Systems Duality

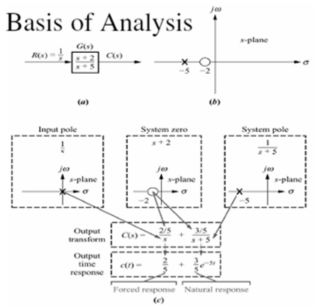
Primal	Dual
Linear	Nonlinear
Continuous-Time	Discrete Time
Time Invariant	Time Varying
Deterministic	Stochastic
Model Based	Non-Model Based

Introduction to Control Systems

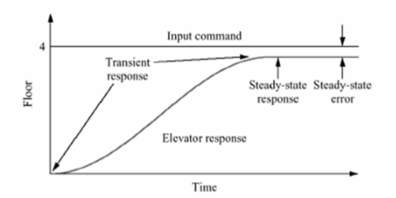
Review on Fundamental Control System

- Mathematics for Dynamic Systems
  - Differential Equation
  - Transfer Function
  - State Space
- Time Response
  - Transient
  - Steady State
- Frequency Response
  - Bode and Nyquist Plots
  - Stability and Stability Margins

Introduction to Control Systems



Introduction to Control Systems

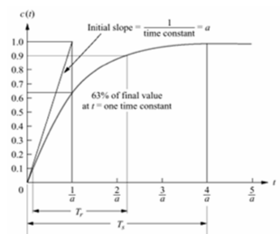


System order = ?

Introduction to Control Systems

First Order Transfer Function

$$G(s) = \frac{a}{(s+a)} = \frac{1}{(\tau s + 1)}$$



Settling time = 4 τ

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Second order transfer function:

$$G(s) = \frac{1}{\left(\frac{s}{\omega_n}\right)^2 + 2\xi\left(\frac{s}{\omega_n}\right) + 1}$$

ξ : damping ratio, ω_n : natural frequency

$\xi > 1$: overdamped

$\xi < 1$: underdamped

$\xi = 1$: critically damped

$\xi = 0$: undamped

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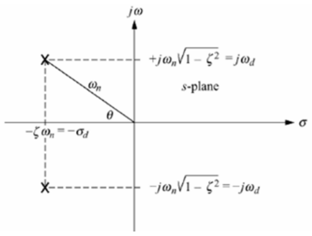

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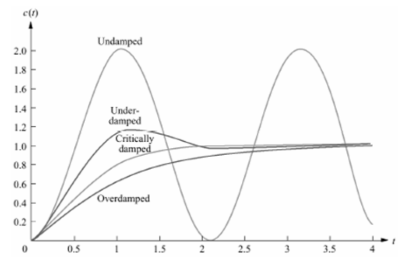

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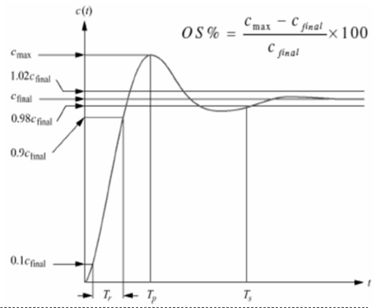
$$OS\% = e^{-(\zeta\pi/\sqrt{1-\zeta^2})} \times 100$$

$$T_s = \frac{4}{\zeta\omega_n}$$



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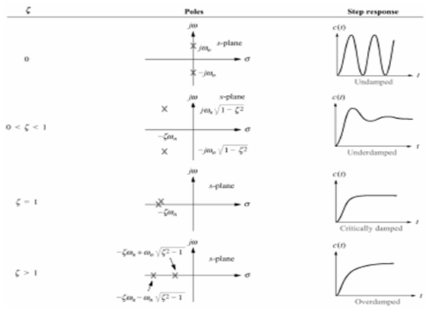

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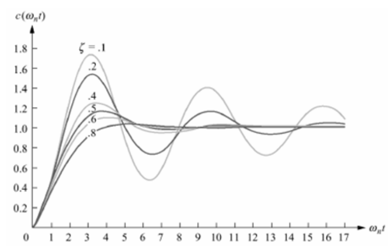

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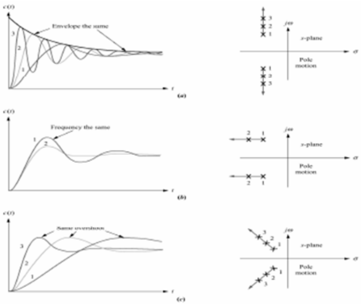

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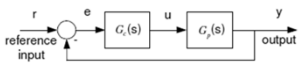
Steady State Error



$$e_{ss} = e(t)|_{t\to\infty} = sE(s)|_{s\to 0}$$

$$E(s) = \frac{R(s)}{1+G_c(s)G_p(s)}$$

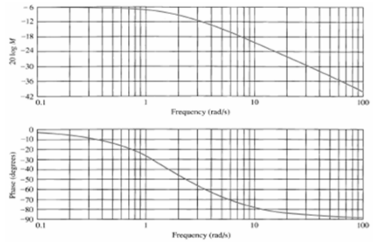
Introduction to Control Systems

Frequency Response:
The MOST useful concept in control theory

- Performance Measures
  - Bandwidth
  - Disturbance Rejection
  - Noise Sensitivity
- Stability
  - Yes or No?
  - Stability Margins (closeness to instability)
  - Robustness (generalized stability margins)

Introduction to Control Systems

Bode Plot (Magnitude and Phase vs. Frequency) G(s) =1/(s +2)



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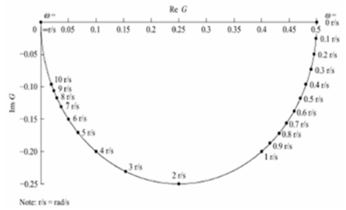
Polar Plot: imaginary part vs. real part of G(jω) G(s) =1/(s +2)



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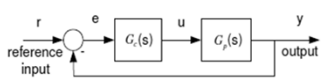
Bandwidth of Feedback Control



- -3dB Frequency of CLTF $\frac{Y(j\omega)}{R(j\omega)} = \frac{G_c(j\omega)G_p(j\omega)}{1+G_c(j\omega)G_p(j\omega)}$
- 0 dB Crossing Frequency (ω_c) of $G_c(j\omega)G_p(j\omega)$
- Defines how fast y follows r

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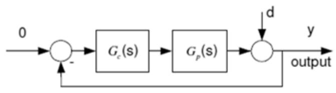
Disturbance Rejection



$$\frac{Y(j\omega)}{D(j\omega)} = \frac{1}{1+G_c(j\omega)G_p(j\omega)}$$

measures disturbance rejection quality

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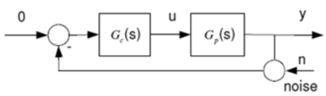
Noise Sensitivity

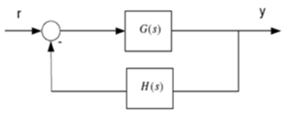


$$\frac{U(j\omega)}{N(j\omega)} = \frac{-G_c(j\omega)}{1+G_c(j\omega)G_p(j\omega)}$$
$$\approx -G_c(j\omega) \text{ at high frequency}$$

Introduction to Control Systems

Nyquist Plot

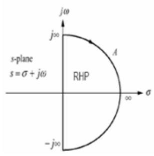
Using G (jω) to determine the stability of



$G(s) = G_c(s)G_p(s)$

$H(s)$: Sensor and Filter

Nyquist Contour



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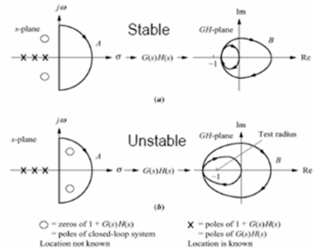
Nyquist Stability Criteria



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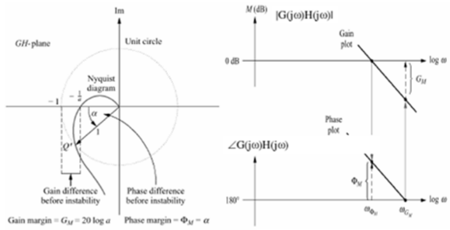
Gain and Phase Margins

(-1,0) is equivalent of $0\text{db}\angle(-180)^\circ$ point on



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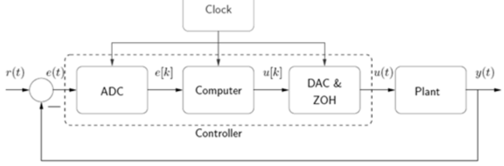
Computer-Controlled Systems



ADC - Analog-Digital-Converter (includes sampler), DAC - Digital Analogue Converter, ZOH - Zero Order Hold

Introduction to Control Systems

Digital Control Concepts

- Sampling
  - Rate
  - Delay
- ADC and DAC
  - Resolution (quantization levels)
  - Speed
  - Aliasing
- Digital Control Algorithm

  Difference equation

Introduction to Control Systems

Discrete System Description

- Discrete system

  $u[n] \rightarrow \boxed{h[n]} \rightarrow y[n]$

  $h[n]$: impulse response

- Difference equation

$$\sum_{k=0}^{N} a_k\, y[n-k] = \sum_{k=0}^{M} b_k u[n-k]$$

Introduction to Control Systems

Discrete Fourier Transform and z-Transform

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega}$$

$$X(z) = \sum_{n=-\infty}^{\infty} x[n] z^{-n}$$

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Discrete Transfer Function and Frequency Response

$$H(z) = \frac{Y(z)}{X(z)} = \frac{\sum_{k=0}^{M} b_k z^{-k}}{\sum_{k=0}^{N} a_k z^{-k}}$$

$$H(e^{j\omega}) = H(z)|_{z=e^{j\omega}}$$

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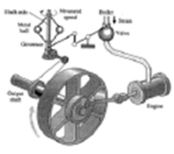
History of Automatic Control

A.D.

- **1770s (Feedback control)**
- **1769 Jams Watt : steam engine (flyball governor)**



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History of Automatic Control

- 1868 J.C. Maxwell : stability analysis of dynamic system, Cambridge University.
- 1877 E.J. Routh : stability of high order system
- 1907 A.M. Lyapunov : stability of equation of motion (state space form Poincare' 1892)


James Clerk Maxwell (1831–1879)


Edward John Routh (1831-1907)


Aleksandr Mikhailovich Lyapunov 1857-1918

Introduction to Control Systems

History of Automatic Control

- 1913 H. Ford : automation
- 1927 H.W. Bode : feedback amplifier analysis (frequency domain approach)
- 1932 H. Nyquist: stability criterion for frequency domain approach
- 1936 Callender : PID controller
- 1948 W.R. Evens : the root locus approach


Hendrik Wade Bod (1905-1982)


Harry Nyquist (1889-1976)


Walter R. Evans (1920-1999)

Introduction to Control Systems

History of Automatic Control (Cont.)

- 1950s (Optimal control)
- 1952 MIT: NC machine
- 1954 robotic control
- 1956 Bellman : dynamic programming (USA)
- 1960 Kalman : MIMO problem controllability & observability
- 1961 Kalman & Bucy : Kalman-Bucy filter

Introduction to Control Systems

History of Automatic Control (Cont.)

- 1963 Pontryagin : maximum principle, time optimal controller and optimal controls for linear systems with a quadratic cost function
- 1964 Kalman : design procedure for linear optimal control problem with quadratic performance criterion

- 1970s (Frequency domain design method for MIMO systems)
- 1969 Rosenbrock : inverse Nyquist array method
- 1970 MacFarlane, Postlethwaite, Edmunds and Kovaritakis : Characteristic locus method

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History of Automatic Control (Cont.)

- 1976 Youla : stable factorization technique
- 1983 Zames & Francis : H-infinity control theory
- 1984 Barmish : robust stability with structure physical parameter perturbations
- 1986 M. Athans : LQG/LTR design method

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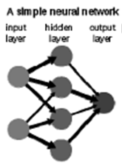
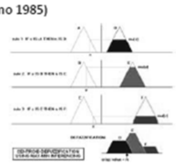
History of Automatic Control (Cont.)

- 1990s (Intelligent control)
- 1990 Astrom : Expert control

Fuzzy control (Zadeh 1964, Mamdani 1976, Sugeno 1985)

Neural networks





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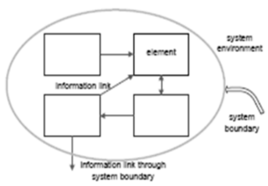
- General system

A system is a collection of components which interact with each other and with the environment (by information or energy links) from which the system is separated by a notational boundary.



Introduction to Control Systems

Problems Formulation

- ***Control system***
  A control system is a system capable of *monitoring* and *regulating* the operation of a process or a plant. The study of control system is essentially a study of an important aspect of systems engineering and its applications.

- ***Problem formulation***
  Determine a control law to *stabilize* the system and to achieve
  asymptotic reference tracking and *disturbance rejection*.

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Introduction to Control Systems

(a) The F-18 aircraft, one of the first production military fighters to use "fly-by-wire" technology, and

(b) the X-45 (UCAV) unmanned combat aerial vehicle. (Photographs courtesy of NASADryden Flight Research Center.)

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Introduction to Control Systems

Control Engineering Practice

- Control engineering is concerned with the analysis and design of goal-oriented (task-oriented) systems. Control systems are used to achieve
  - increased productivity and
  - improved performance.

- ***Main tasks of control engineering***
  Modelling, Analysis, Design and Development.

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Introduction to Control Systems

- *Automation*

  The control of industrial process (manufacturing, production, etc.) by automatic rather than manual means is called automation.

- *Robust control*

  The system can be controlled by the controller in a desired manner, in spite of the allowable disturbances and changes in the system parameters/ uncertainties.

- *Intelligent control system*

  The system has capabilities of planning, scheduling, adaptation, and learning.

Introduction to Control Systems

Control System Design

Engineering design is the main task of the engineer.

Specifications

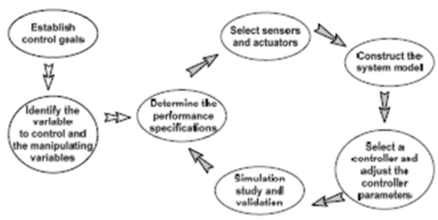
The closed-loop control system performance specifications include:

1) good regulation against disturbance,
2) desirable responses to commands,
3) realistic actuator signal,
4) low sensitivity, and
5) robustness

The *design* is to achieve appropriate design specifications and rests on four characteristics: complexity, tradeoffs, gaps and risk.

Introduction to Control Systems

Design Process



Introduction to Control Systems

Classifications of control systems:

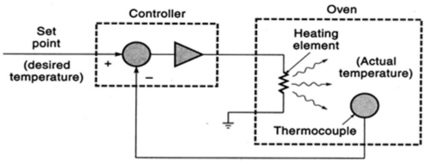
1) ***Regulatory System*** (process control)
Maintains a parameter at or near a setpoint

2) ***Follow-up System*** (servomechanism)
Causes the output to follow a predefined path.

3) ***Event Control System***
Controls a sequential series of events.

Introduction to Control Systems

1) Process control refers to a control system that oversees some industrial processes so that a uniform, correct output is maintained. Control variables are: temperature, flow, level, and pressure of liquids and gases.



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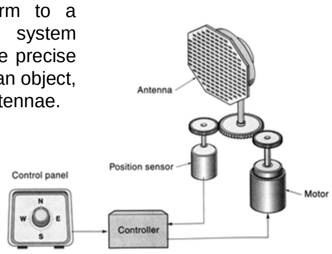
2) Servo Control Traditional term to a closed-loop system that directs the precise movement of an object, such as an antennae.



Introduction to Control Systems

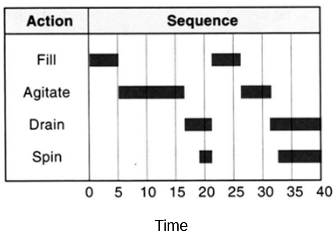
3) Sequentially Controlled Systems

- A series of defined tasks to be performed.
- Time-Driven

  Each operation in the sequence is performed for a certain amount of time. May be open-loop control.
- Event-Drive:

  Each operation is performed until some event goal is reached. Must be closed-loop control.

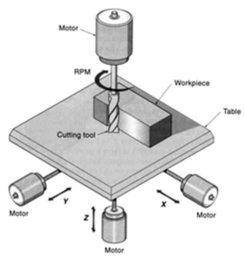
Introduction to Control Systems



Introduction to Control Systems

Numerical Control: type of digital control on machine tools which use a numeric coordinate system to define the movement of components, typically in X,Y, Z coordinates.

Today's systems can accept data directly from CAD drawing information for the control of the operation. **Computer-aided Manufacturing (CAM).**



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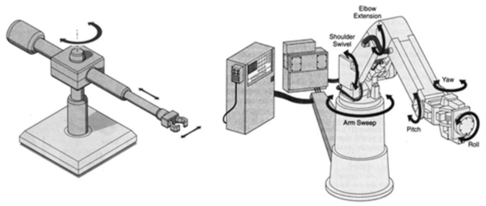
Pick-and-place robots



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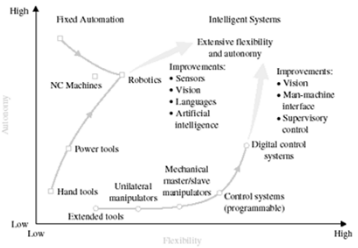
Future of Control systems



Introduction to Control Systems

Journals

Automatica.
Control Engineering Practice.
IEEE Control Systems Magazine.
IEEE Transactions on Automatic Control.
IEEE Transactions on Control Systems Technology.
International Journal of Control.
International Journal of Robust and Nonlinear Control.
Journal of Dynamic Systems, Measurement and Control.
Journal of Process Control.
Mechatronics.
SIAM Journal on Control and Optimization.
Systems and Control Letters.
Transactions of the Institute of Measurement and Control.