ADVANCED CONTROL SYSTEM DESIGN FOR AEROSPACE APPLICATIONS

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Course Objective

- To study concepts and techniques of linear and nonlinear control system analysis and synthesis in state space framework.
- It will have preferential bias towards aerospace applications, especially towards aircrafts and missiles.
- However, the theory as well as many demonstrative examples studied in this course will be generic.

Topics Covered (Syllabus)

- Introduction and Motivation
- First and Second Order Linear ODEs
- Laplace Transform, Transfer Function and Selected Topics from Classical Control
- Introduction to Basic Flight Mechanics and Flight Control Systems
- State Space Representation of Dynamical Systems
- Linearization of Nonlinear Systems

Topics Covered (Syllabus)

- Review of Matrix Theory
- Applications of Numerical Methods in Systems Engineering
- Time Response of Dynamical Systems in State Space Form
- Stability, Controllability and Observability of Linear Systems
- Pole Placement Control Design
- Pole Placement Observer Design
- Static Optimization

Topics Covered (Syllabus)

- Optimal Control Formulation: Variational Calculus Approach
- Linear Quadratic Regulator (LQR) Design
- Application of Linear Control Theory to Autopilot Design of Aircrafts and Missiles
- Gain Scheduling Philosophy
- Dynamic Inversion Design
- Stability Analysis of Nonlinear Systems Using Lyapunov Theory

Topics Covered (Syllabus)

- Neuro-Adaptive Design for Nonlinear Systems
- Advanced Nonlinear Control of Aerospace Vehicles Using Dynamic Inversion and Neuro-Adaptive Design
- Back-stepping Design
- An Overview of LQ Observer and Kalman Filtering
- Nonlinear Observer Design

References: Linear Control System

- **N. S. Nise:** *Control Systems Engineering*, 4th Ed., Wiley, 2004.
- **K. Ogata:** *Modern Control Engineering*, 3rd Ed., Prentice Hall, 1999.
- **B. Friedland:** *Control System Design*, Mc.Graw Hill, 1986.
- **M. Gopal:** *Modern Control System Theory*, 2nd Ed., Wiley, 1993.

References: Nonlinear Control Systems

- * **H. J. Marquez:** *Nonlinear Control Systems Analysis and Design*, Wiley, 2003.
- * **J-J E. Slotine and W. Li:** *Applied Nonlinear Control*, Prentice Hall, 1991.
- **H. K. Khalil:** *Nonlinear Systems*, Prentice Hall, 1996.
- **A. Isidori:** *Nonlinear Control Systems, 3rd Ed.*, Springer, 1995.
- * **Current literature**

References for Other Topics

- **A. E. Bryson and Y-C Ho:** *Applied Optimal Control*, Taylor and Francis, 1975.
- **J. L. Crassidis and J. L. Junkins:** *Optimal Estimation of Dynamic Systems, CRC Press, 2004.*
- **W. S. Levine (Ed):** *The Control Handbook*, CRC and IEEE Press, 1996.
- **R. C. Nelson:** *Flight Stability and Automatic Control*, McGraw Hill, 1989.
- **E. Kreyszig:** *Advanced Engineering Mathematics*, 8th Ed., Wiley, 2004.

Lecture – 1

Introduction and Motivation for Advanced Control Design

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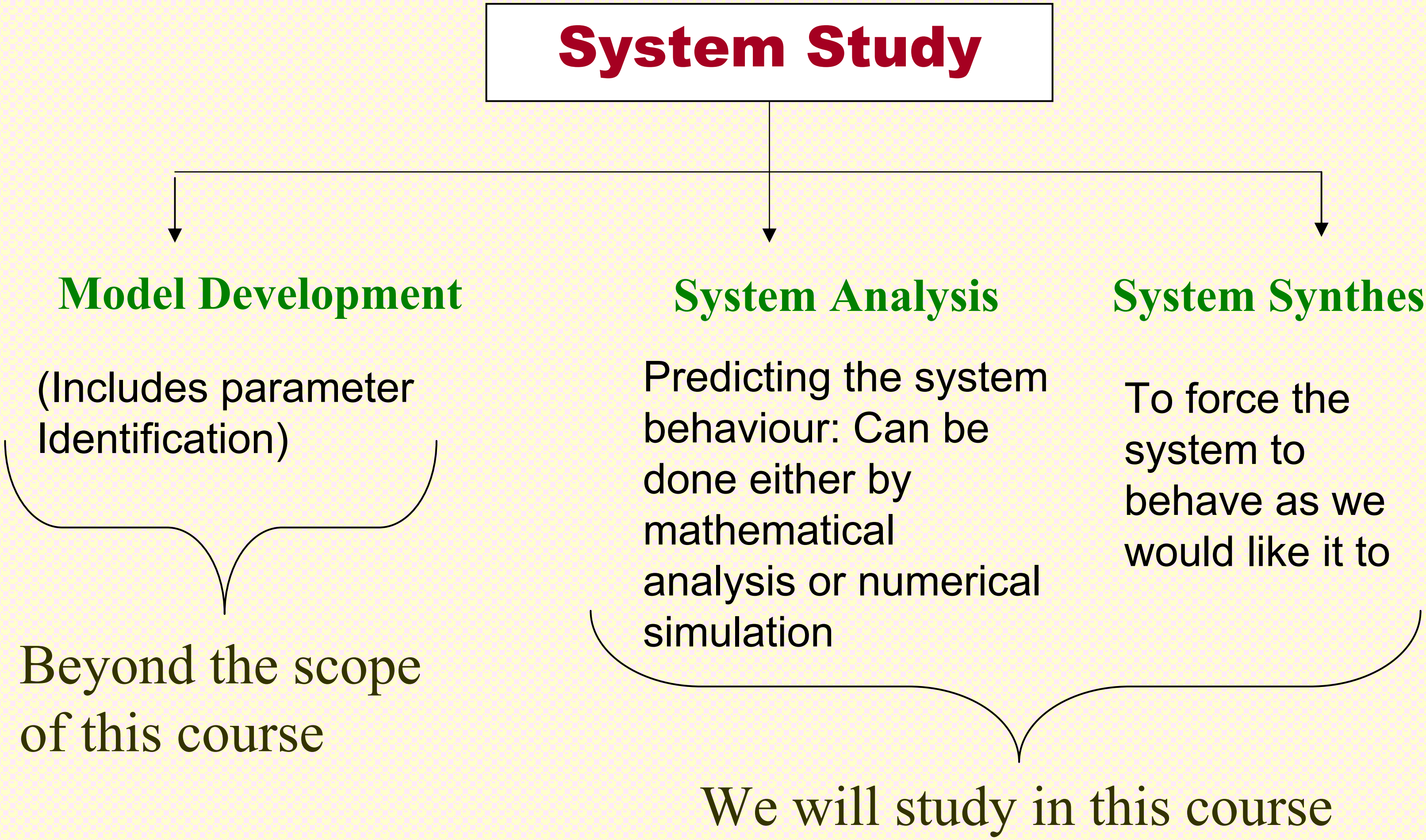
Concepts and Definitions

- **System:** Any collection of interacting elements for which there are cause-and-effect relationships among the variables.
- **Dynamical System:** A system in which the variables are time-dependent.
- **Mathematical Model:** A description of a system in terms of mathematical equations.

Concepts and Definitions

- **System Variables**
  - **Input variables**
    - **Control inputs:** Manipulative input variables (usually known, computed precisely)
    - **Noise inputs:** Non-manipulative (usually unknown)
  - **Output variables**
    - **Sensor outputs:** Variables that are measured by sensors
    - **Performance outputs:** Variables that govern the performance of the system (**Note:** Sensor and performance outputs may or may not be same)
  - **State variables:** A set of variables that describe a system completely (will be studied in detail later)

Classification of System Study



System Study

Model Development

(Includes parameter Identification)

Beyond the scope of this course

System Analysis

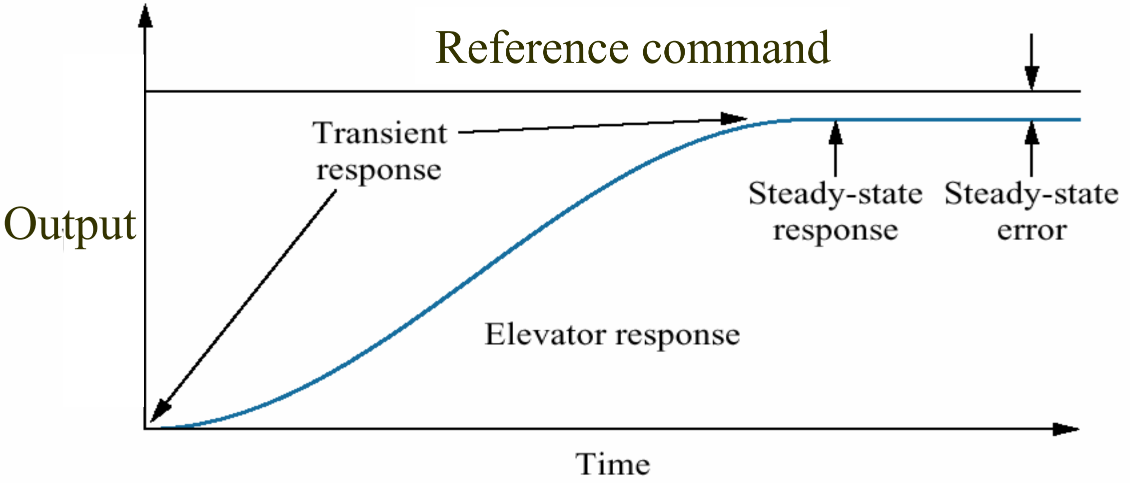
Predicting the system behaviour: Can be done either by mathematical analysis or numerical simulation

System Synthesis

To force the system to behave as we would like it to

We will study in this course

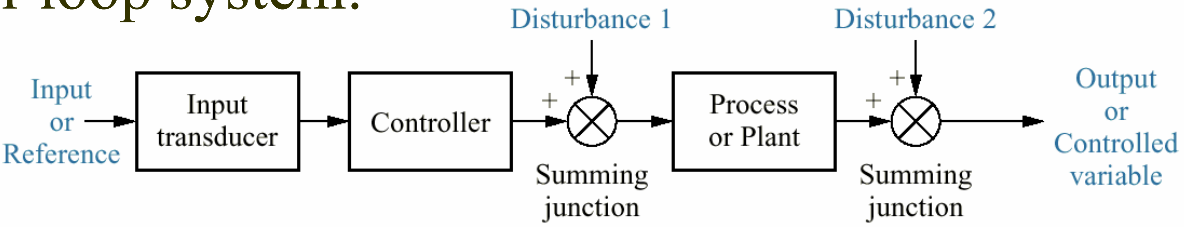
Simplified description of a control system



Ref: N. S. Nise: Control Systems Engineering, 4th Ed., Wiley, 2004

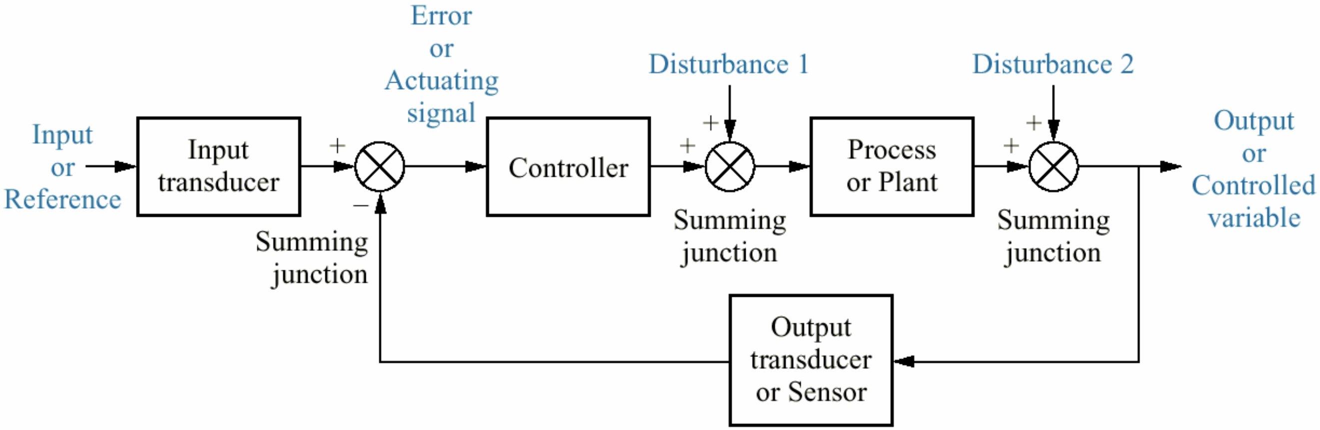
Open-loop vs. Closed-loop System

Open-loop system:



(*a*)

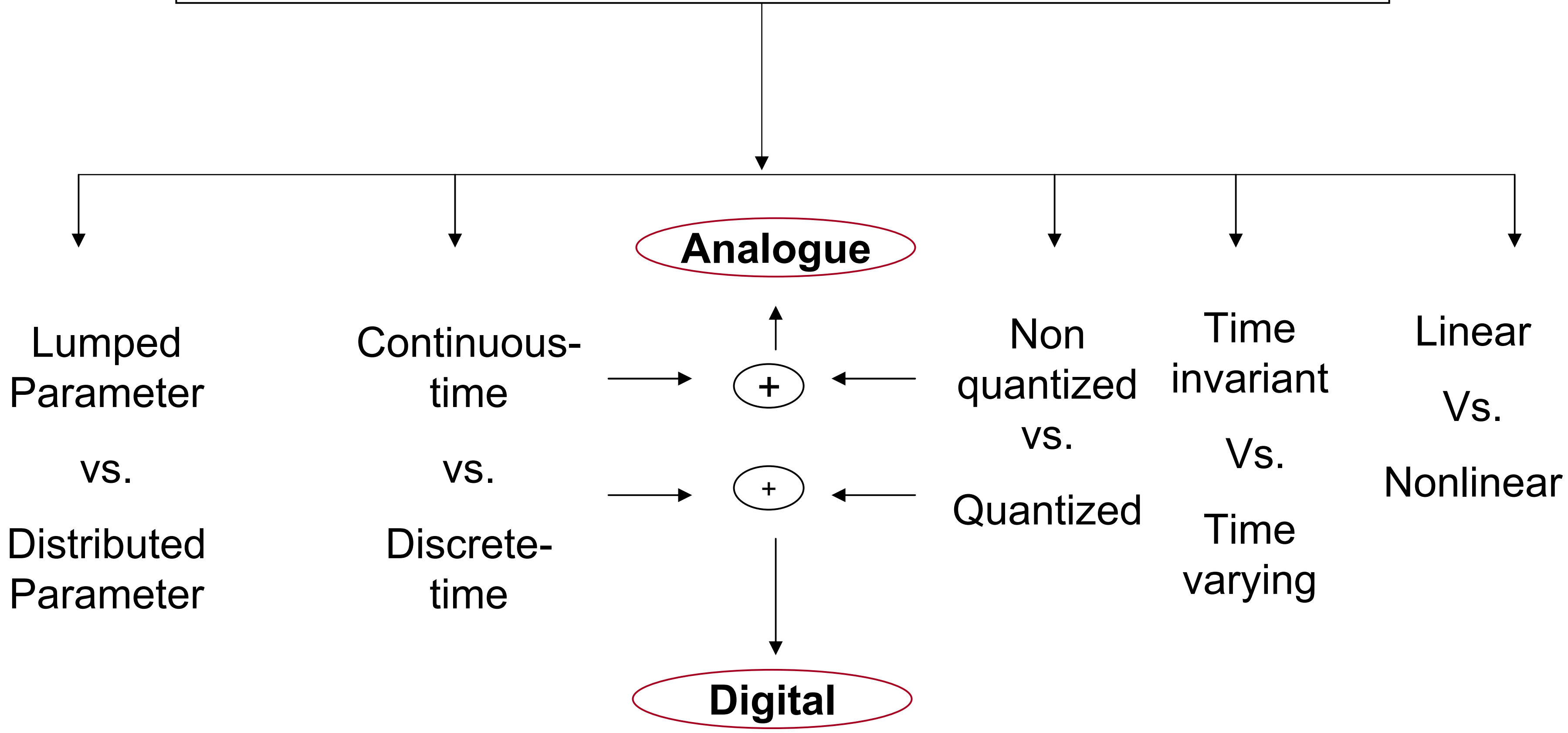
Closed-loop system:



(*b*)

Ref: N. S. Nise: Control Systems Engineering, 4th Ed., Wiley, 2004

System Classification



Lumped Parameter

vs.

Distributed Parameter

Continuous-time

vs.

Discrete-time

Analogue

+

+

Digital

Non quantized
vs.

Quantized

Time invariant

Vs.

Time varying

Linear

Vs.

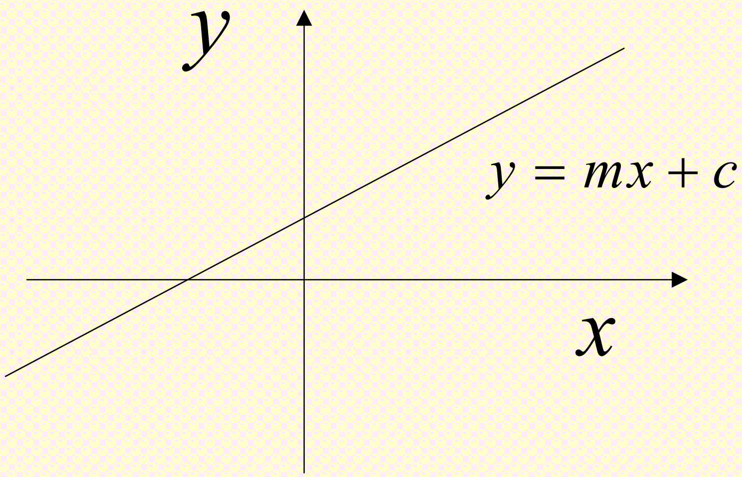
Nonlinear

Linear Systems

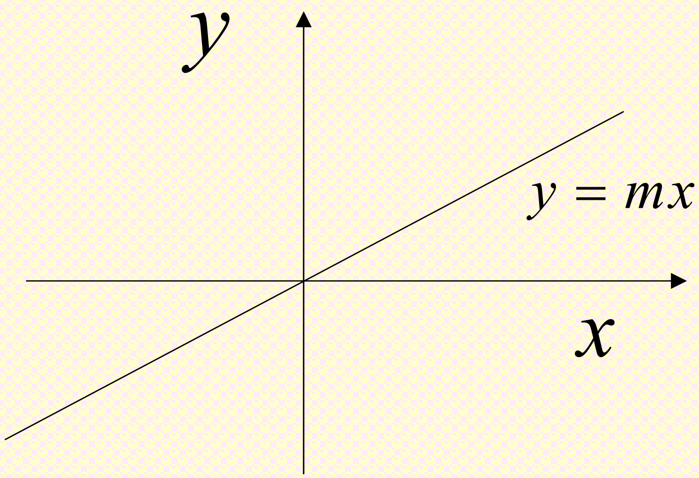
- Linear systems are systems that obey the “**Principle of superposition**”:
  - Multiplying the input(s) by any constant α must multiply the outputs by α.
  - The response to several inputs applied simultaneously must be the sum of the individual responses to each input applied separately.

Example: Static System

Equation of a straight line $y = mx + c$ is "Not Necessarily Linear" unless $c = 0$



(Not linear)



(Linear)

Example: Dynamical System

Example - 1 (Linear System)

$\dot{x} = 2x$

1) $\alpha \dot{x} = \alpha\left(2x\right) = 2\left(\alpha x\right)$

2) $\frac{d}{dt}\left(x_1 + x_2\right) = \dot{x}_1 + \dot{x}_2 = 2x_1 + 2x_2 = 2\left(x_1 + x_2\right)$

Example - 2 (Nonlinear System)

$\dot{x} = 2x + 3$

1) $\alpha \dot{x} = \alpha\left(2x + 3\right) \neq 2\left(\alpha x\right) + 3$

2) $\frac{d}{dt}\left(x_1 + x_2\right) = \dot{x}_1 + \dot{x}_2 = \left(2x_1 + 3\right) + \left(2x_2 + 3\right) \neq 2\left(x_1 + x_2\right) + 3$

Example - 3 (Nonlinear System)

$\dot{x} = 2\sin x$

1) $\alpha \dot{x} = \alpha\left(2\sin x\right) \neq 2\sin\left(\alpha x\right)$

2) $\frac{d}{dt}\left(x_1 + x_2\right) = \dot{x}_1 + \dot{x}_2 = 2\sin x_1 + 2\sin x_2 \neq 2\sin\left(x_1 + x_2\right)$

Nonlinear and Analogous Systems

- Nonlinear systems are systems that are "Not Necessarily Linear"
- Analogous Systems are systems having same mathematical form of the model.
  - However, their variables might have different physical meaning and their parameters might have different numerical values
  - Example: Sping-Mass-Damper and R-L-C systems are analogous

Nonlinear vs. Linear Systems

Nonlinear Systems	Linear Systems
More realistic	Approximation to reality
Usually difficult to analyze and design	Usually simpler to analyze and design
Tools are under development	A lot of tools are well-developed.
Can have multiple equilibrium points	Only single equilibrium point
System stability depends on Initial condition (IC)	Stability nature is independent of IC (justifies the Transfer function approach, where “zero” ICs are assumed)
Limit cycles (self-sustained oscillations)	No limit cycles
Bifurcations (number of equilibrium points and their stability nature can vary with parameter values)	No bifurcation
Chaos (very small difference in I.C. can lead to large difference in output as time increases. That’s why predicting weather for a long time is erroneous!)	No chaos
Frequency and amplitude can be coupled	Frequency and amplitude are independent

Comparison: Classical vs. Modern Control

Classical Control (Linear)	Modern Control (Linear)
Developed in 1920-1950	Developed in 1950-1980
Frequency domain analysis & Design (Transfer function based)	Time domain analysis and design (Differential equation based)
Based on SISO models	Based on MIMO models
Deals with input and output variables	Deals with input, output and **state** variables
Well-developed robustness concepts (gain/phase margins)	Not well-developed robustness concepts
No Controllability/Observability inference	Controllability/Observability can be inferred
No optimality concerns	Optimality issues can be incorporated
Well-developed concepts and very much in use in industry	Fairly well-developed and slowly gaining popularity in industry

+

Linear Robust Control Design

(Fairly well developed….lot of research has been done in 1980s and 1990s).

Some Lessons to Remember

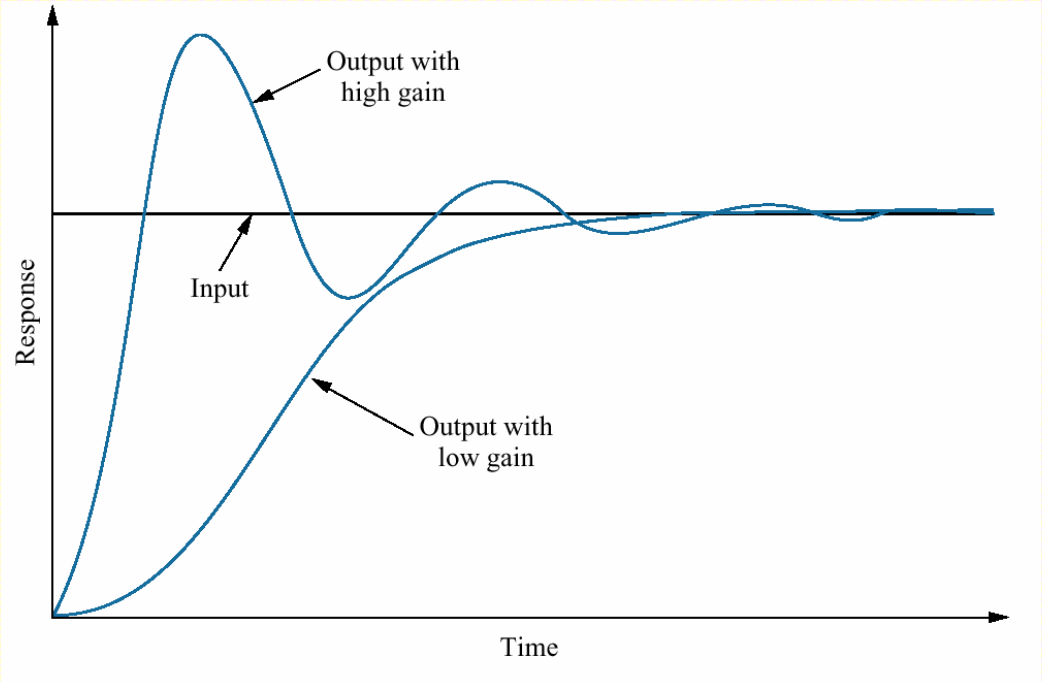
Reference: D. S. Bernstein, A Student's Guide to Classical Control

- Feedback is pervasive
- Block diagrams are not circuit diagrams
- Determine equilibrium points and linearize if necessary
- Check stability: Nominal stability is an absolute necessity… if necessary, guarantee nominal stability through control design
- Robust stability is best, but difficult to obtain
- After stability, performance is everything

Some Lessons to Remember

Reference: D. S. Bernstein, A Student's Guide to Classical Control

- High controller gain
  - Good benefits: Robust stability, Good tracking
  - Bad effects: Control saturation, Noise amplification



Some Lessons to Remember

Reference: D. S. Bernstein, A Student's Guide to Classical Control

- Beware of lightly damped poles
- Time delays can be deadly
- **Respect the unstable mode**
- Nonlinearities are always present
- Peoples lives and/or country's pride may be at stake!

Benefits of Advanced Control Theory

- MIMO theory: Lesser assumptions and approximations
- Simultaneous disturbance rejection and command following (conflicting requirements)
- Robustness in presence of parameter variations, external disturbances, unmodelled dynamics etc.
- Fault tolerance
- Self-autonomy

Benefits of Advanced Control Theory

- **Optimality of the controller**: Incorporation of optimal issues lead to a variety of advantages like minimum cost, maximum efficiency, non-conservative design etc.
- Trajectory planning issues can be incorporated into the control design.
- State and control bounds can be incorporated in the control design process explicitly.
- Integrated designs can replace the traditional outer loop – inner loop designs: Can lead to better performance

Why Nonlinear Control?

- Improvement of existing control systems (neglected physics can be accounted for)
- Explicit account of “hard nonlinearities” and “strong nonlinearities”
  - **Hard nonlinearities: Discontinuity in derivatives (saturation, dead zones, hysteresis etc.)**
  - **Strong nonlinearities: Higher-order terms in Taylor series**
- Can directly deal with model uncertainties
- Can lead to “design simplicity”
- Can lead to better Cost & Performance optimality

Techniques of Nonlinear Control Systems Analysis and Design

- Phase plane analysis
- Lyapunov theory
- Differential geometry (Feedback linearization)
- Intelligent techniques: Neural networks, Fuzzy logic, Genetic algorithm etc.
- Describing functions
- Optimization theory (variational optimization, dynamic programming etc.)

Advanced Control Theory:
Some Applications in Aerospace Engineering

Ref. C. F. Lin: *Advanced Control Systems Design*, Prentice Hall, 1994.

- Missile Guidance and Control
    - Rapid and precise command response
    - Robustness against unmodelled dynamics and/or parameter variations
    - Multivariable design is required due to high coupling
    - System limitations (like tail-control and smaller fins)
    - Disturbance rejection (wind gust, engine ignition and burnout, stage separation etc.)

Advanced Control Theory:
Some Applications in Aerospace Engineering

- Aircraft Flight Control
  - Stability augmentation
  - Configuration management
  - Maneuver enhancement
  - Maneuver limiting
  - Load alleviation
  - Structural mode control
  - Buffet alleviation (especially for twin-tail aircrafts)
  - Flutter margin augmentation

Advanced Control Theory:
Some Applications in Aerospace Engineering

- Guidance and Control of Unmanned Air Vehicles (UAVs)
  - Reconnaissance
  - Aiding to warfare capability
  - Experimental research (for advanced technologies)
  - Autonomous mission
  - Meteorological data collection
  - Search and Rescue
  - Other “interesting” applications (like movie recording)

Thanks for the Attention…!