西安交通大學

School of Electrical Engineering

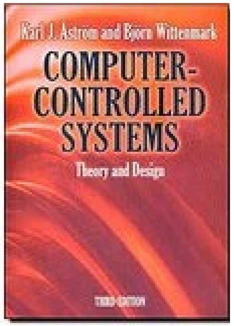
Digital Control Technique

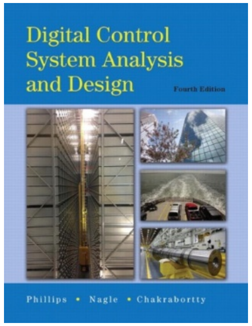
Chapter 1
Introduction

Kou Peng

Course Information

- Time: 16:40-18:30, Monday
  14:30-16:20, Thursday
- Venue: #326, #1 East Building
- Modules + Experiments
- Text book:
  - K. J. Astrom, Computer control system: theory and design
  - C. Phillips, et al., Digital control system analysis and design
  - 康波, 计算机控制系统





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  #4197, Gongxing Building

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1.1 Control Problem

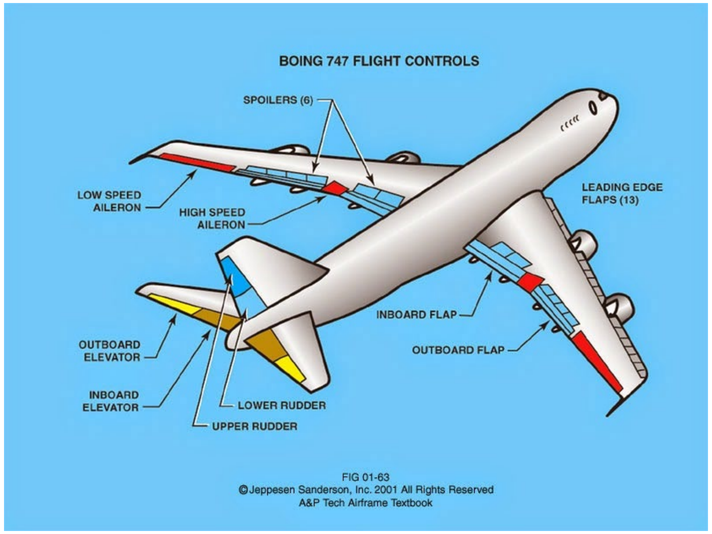
What do these two have in common?

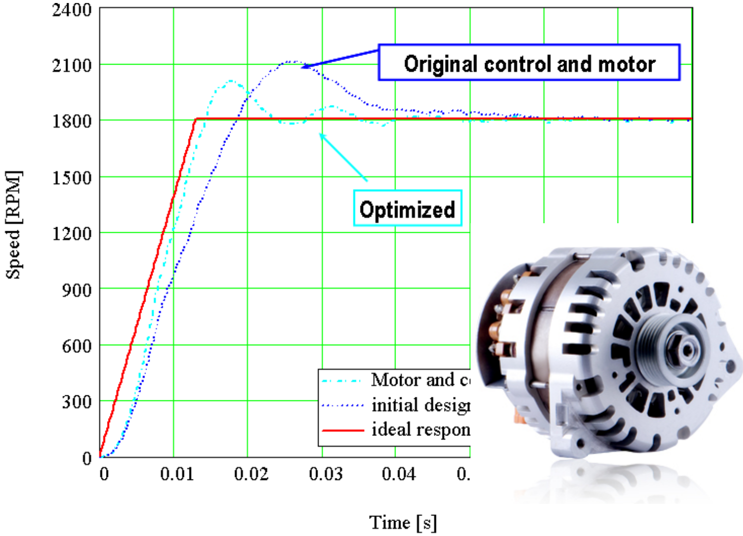
- Highly nonlinear, complicated dynamics!
- Both are capable of transporting goods and people over long distances

BUT

- One is controlled, and the other is not.

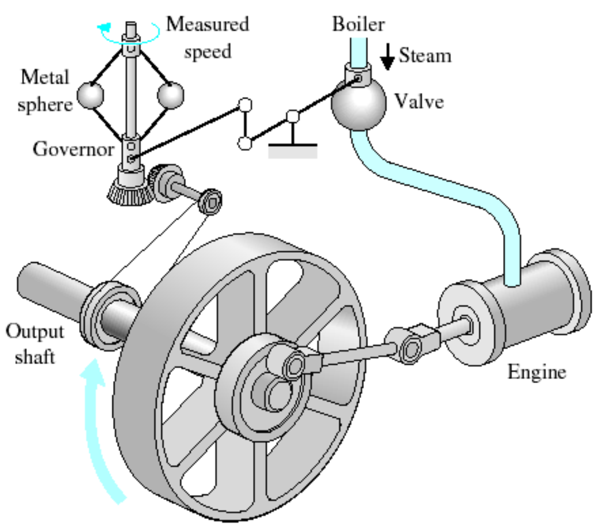
- Why do we need control system
  - Industrial processes are not static but rather very dynamic; they are continuously changing as a result of many types of disturbances
  - Every process has inertia in some degree

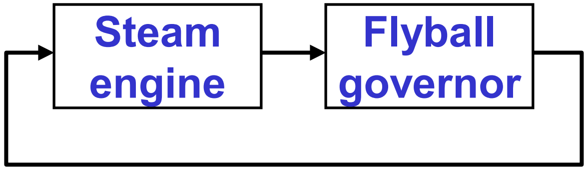


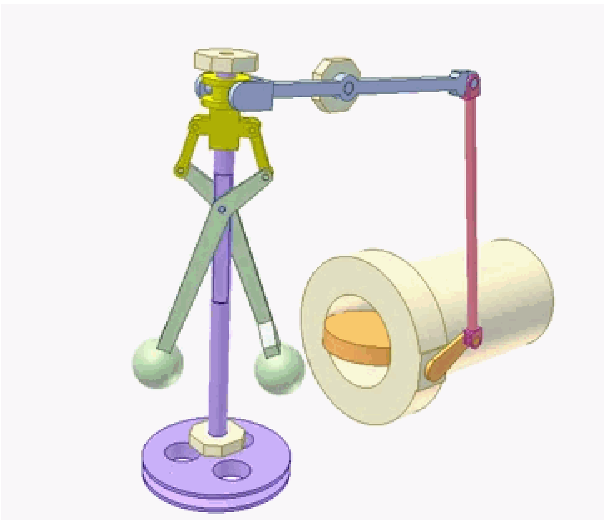


  - It is principally because of this dynamic and inertia nature that control systems are needed to continuously and automatically watch over the variables that must be controlled

- Fundament of modern control system
  - Feedback
    - Miriam Webster: the return to the input of a part of the output of a machine, system, or process (as for producing changes in an electronic circuit that improve performance or in an automatic control device that provide self-corrective action) [1920]

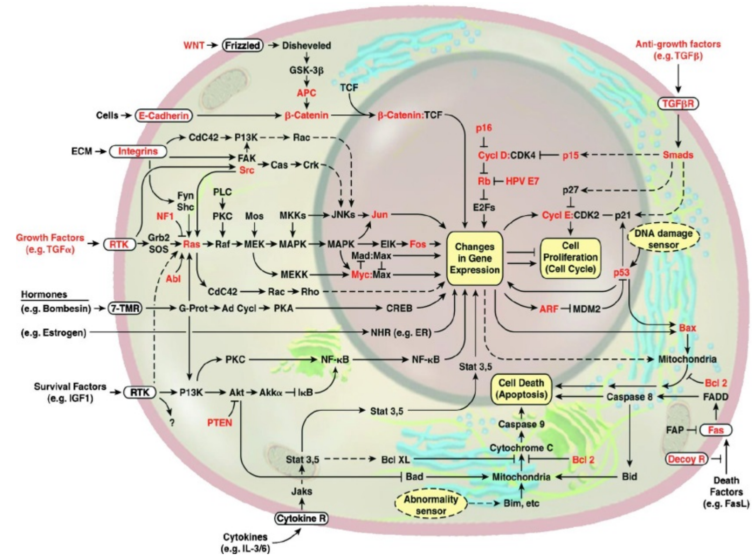




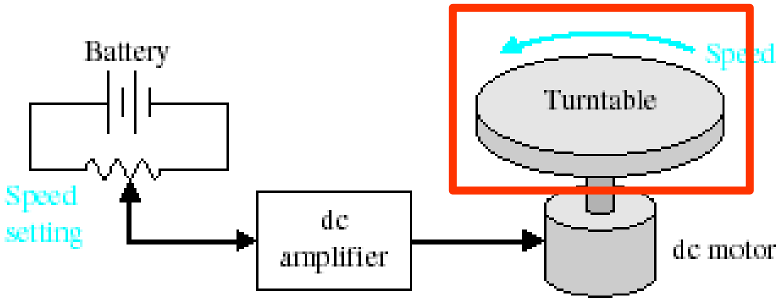


Other Examples of Feedback

- Biological Systems
  - Physiological regulation (homeostasis)
  - Bio-molecular regulatory networks
- Population
  - Family planning
  - Two children policy
- Financial Systems
  - Markets and exchanges
  - Investment

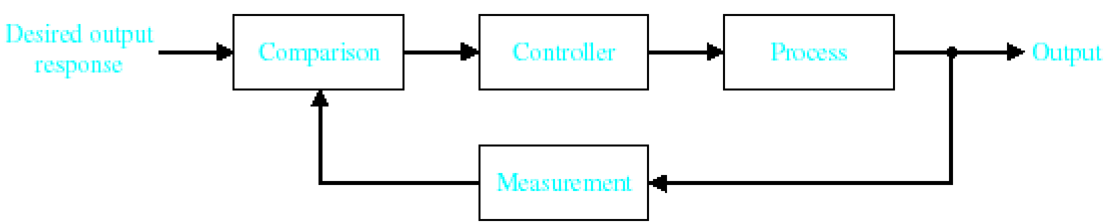


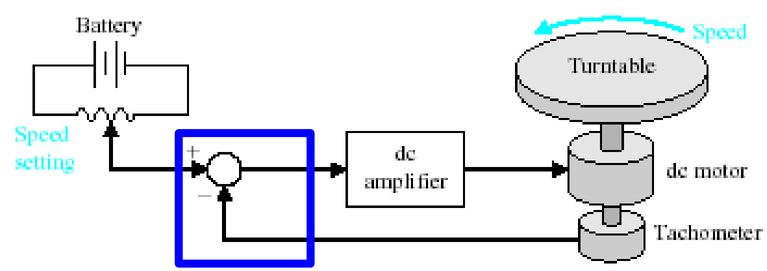
- Open-loop and closed-loop control
  - Open-Loop
    - Control Systems utilize a controller or control actuator to obtain the desired response



  - Closed-Loop
    - Control Systems utilizes feedback to compare the actual output to the desired output response

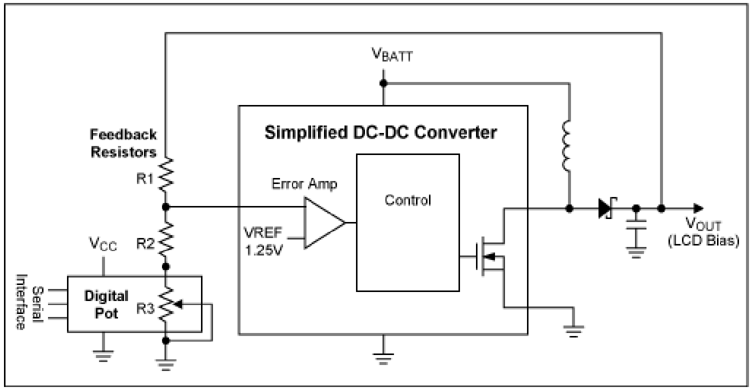
Robust



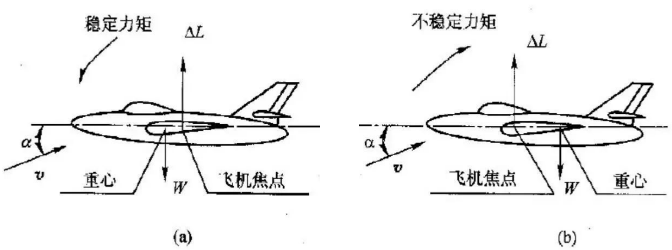


Two main advantages of closed loop control

- Robustness to uncertainty through Feedback
  - Feedback allows high performance in the presence of uncertainty
  - Example: DC-DC converter with varying load
  - Key idea: accurate sensing to compare actual to desired, correction through computation and actuation
- Design of dynamics through feedback
  - Feedback allows the dynamics of a system to be modified
  - Example: stability augmentation for highly agile, unstable aircraft
  - Key idea: interconnection gives closed loop that modifies natural behavior



X-29 experimental aircraft



Close loop control = Sensing + Computation + Actuation

In closed "Loop"

Actuate
Gas Pedal

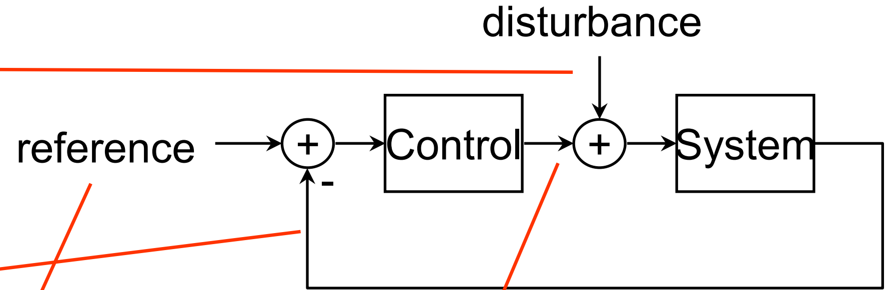
Sense
Vehicle Speed

Compute
Control "Law"

A good controller
A sophisticated driver
A bad controller
An armature

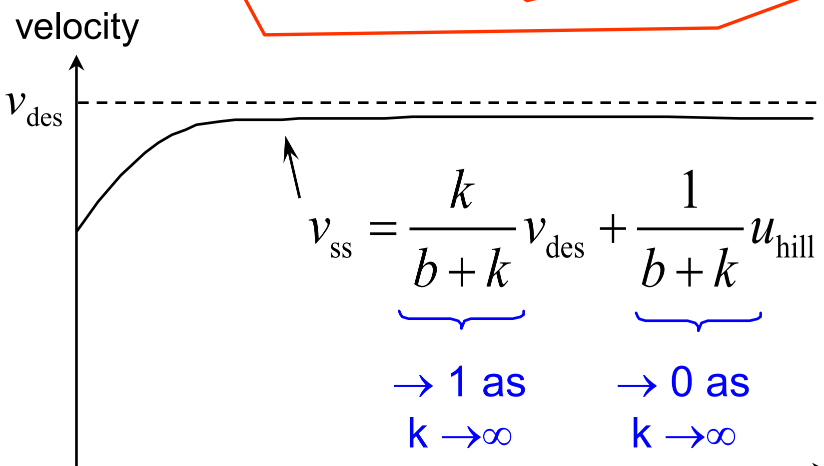
- Goals
  - Stability: system maintains desired operating point (hold steady speed)
  - Accurate: small steady state error (close to 65 mph)
  - Dynamic performance: system responds rapidly to changes (accelerate to 65 mph as soon as possible, overshot as small as possible)
  - Robustness: system tolerates perturbations in dynamics (mass, drag, etc)

- **Control is "the hidden technology that you meet every day"**



Model $m\dot{v} = -bv + u_{\text{engine}} + u_{\text{hill}}$

P Law $u_{\text{engine}} = k(v_{\text{des}} - v)$



Stability/performance

- Steady state velocity approaches desired velocity as $k \to \infty$
- Smooth response; no overshoot or oscillations

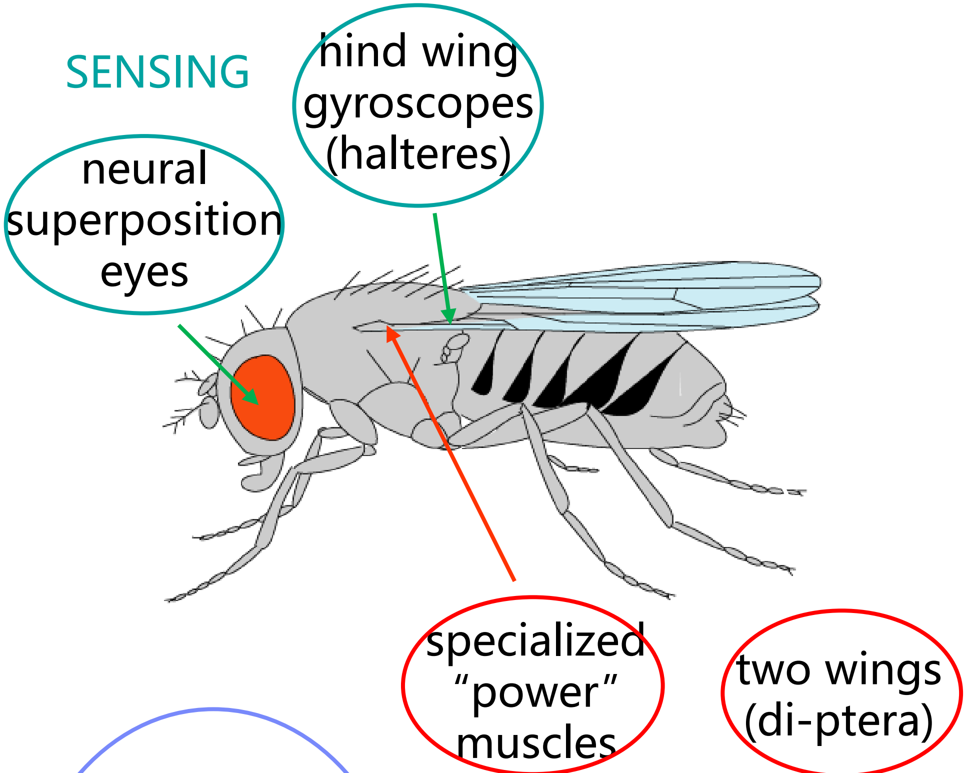
Disturbance rejection

- Effect of disturbances (hills) approaches zero as $k \to \infty$

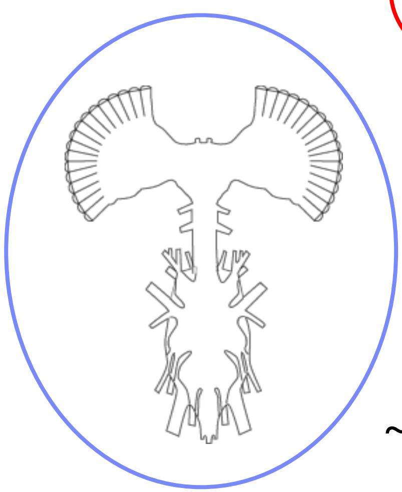
Robustness

- Results don't depend on the specific values of b, m, for k sufficiently large

SENSING

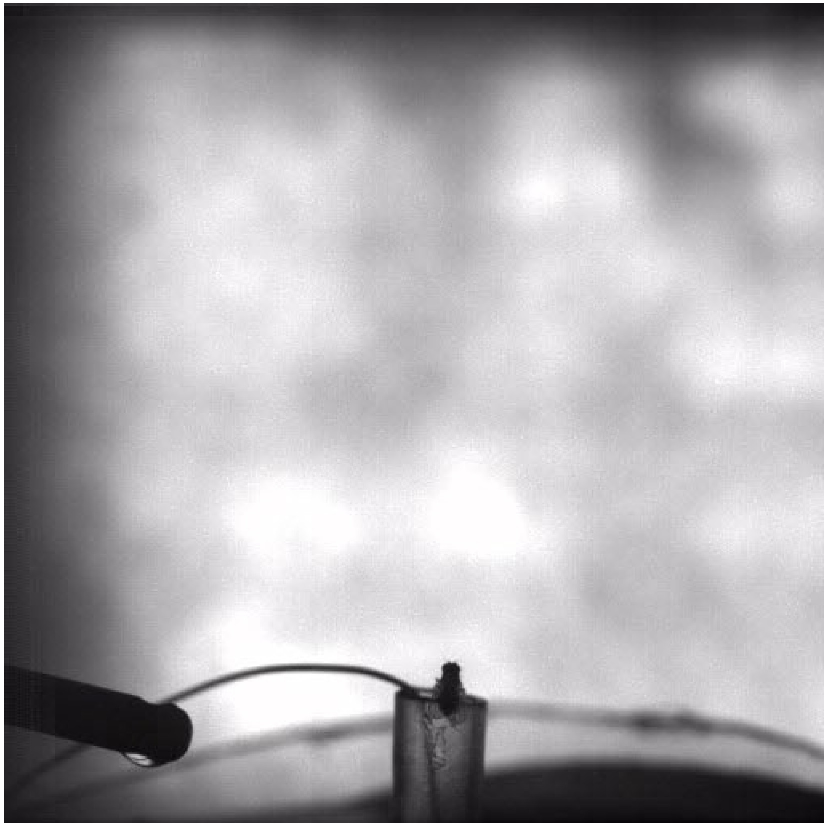


ACTUATION



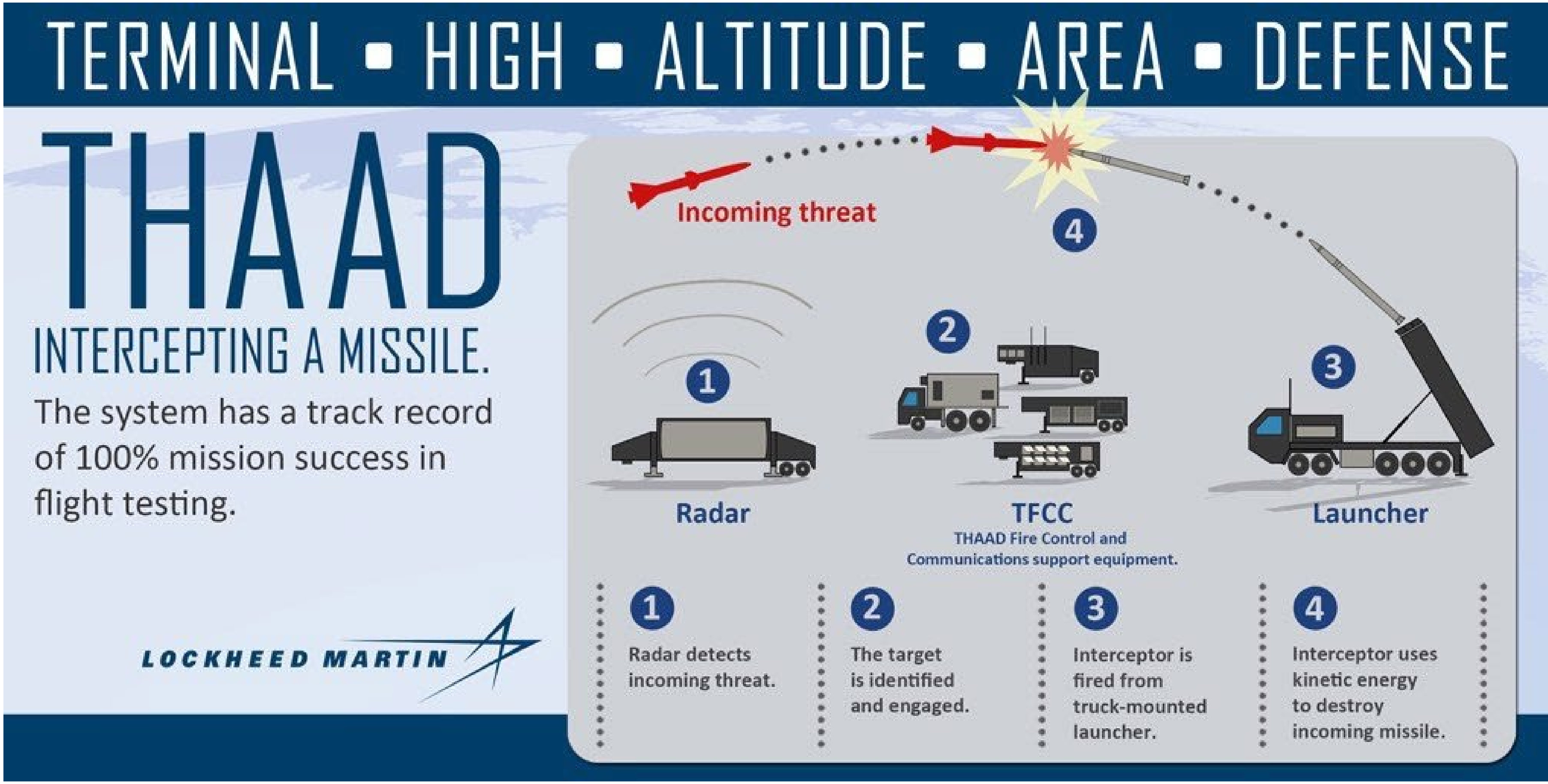
COMPUTATION

~500,000 neurons



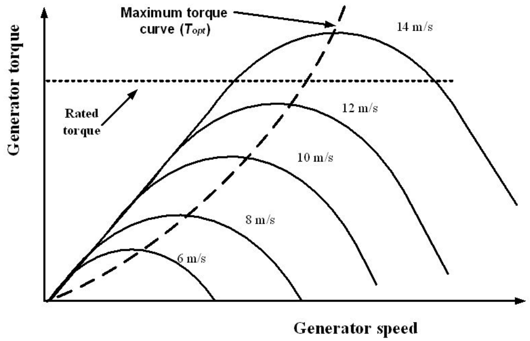
- More information:
  - M. D. Dickinson, Solving the mystery of insect flight, *Scientific American,* June 2001.

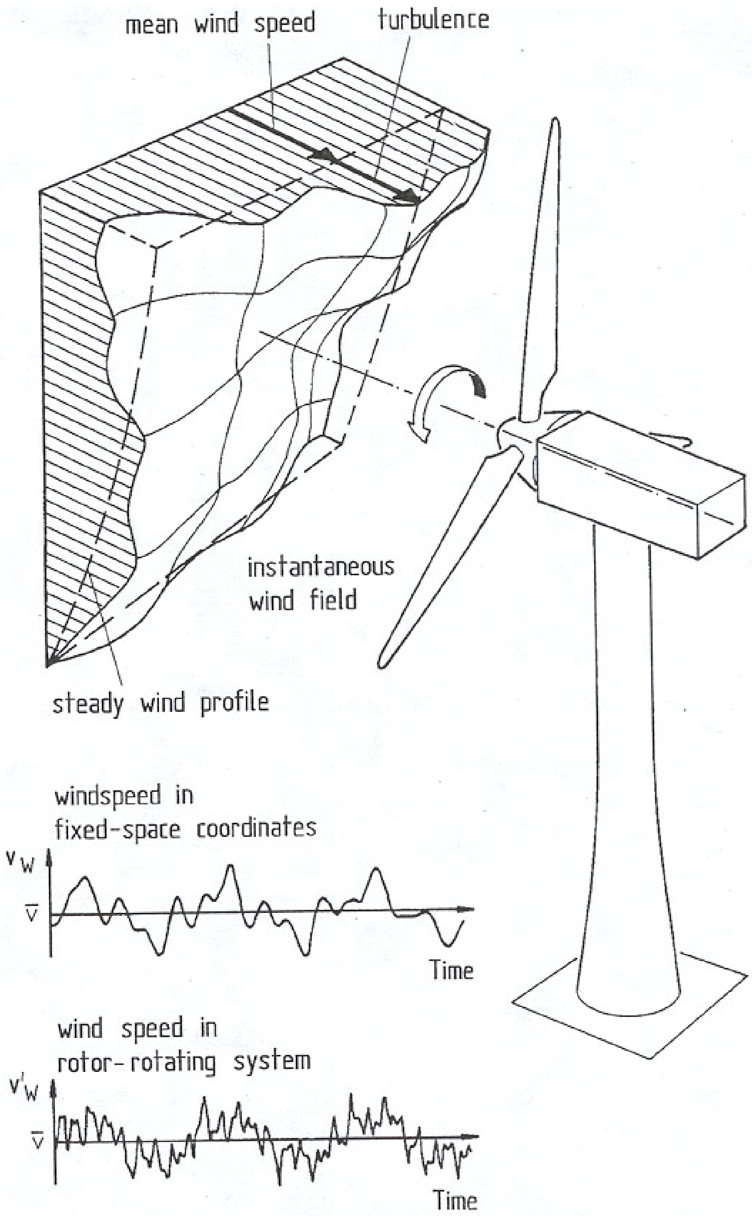
Missile

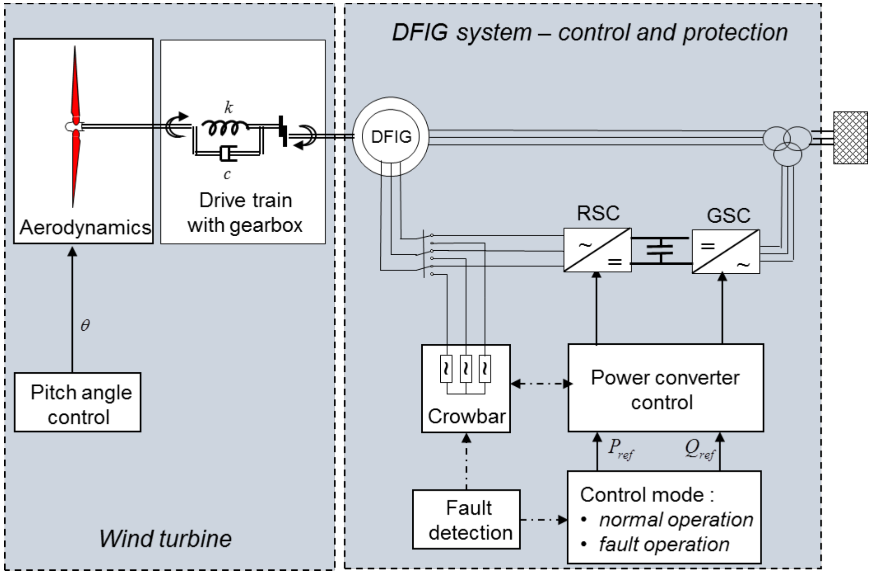

TERMINAL • HIGH • ALTITUDE • AREA • DEFENSE
THAAD
INTERCEPTING A MISSILE.
The system has a track record of 100% mission success in flight testing.
LOCKHEED MARTIN
Incoming threat
4
1
2
3
Radar
TFCC
THAAD Fire Control and Communications support equipment.
Launcher
1 Radar detects incoming threat.
2 The target is identified and engaged.
3 Interceptor is fired from truck-mounted launcher.
4 Interceptor uses kinetic energy to destroy incoming missile.

How to maximum the captured energy under uncertainties?

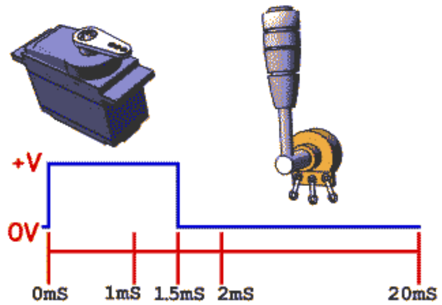
- Stochastic Winds
- Wind Turbulence and Gusts

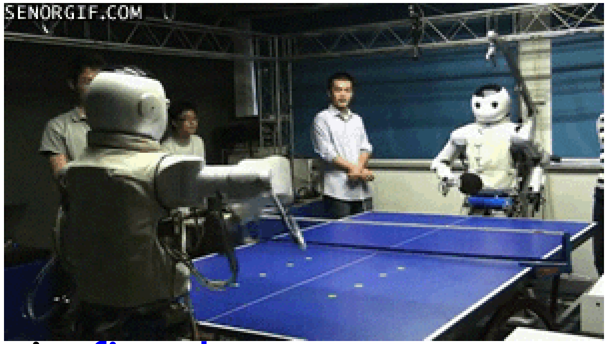






- Control task
  - Servo control - The set-point signal is changed and the manipulated variable is adjusted appropriately to achieve the new operating conditions





  - Regulatory control – The set-point is fixed at a constant value. When any disturbance enters the system, the manipulated variable is adjusted to drive the controlled variable back to its fixed set-point.

Contents

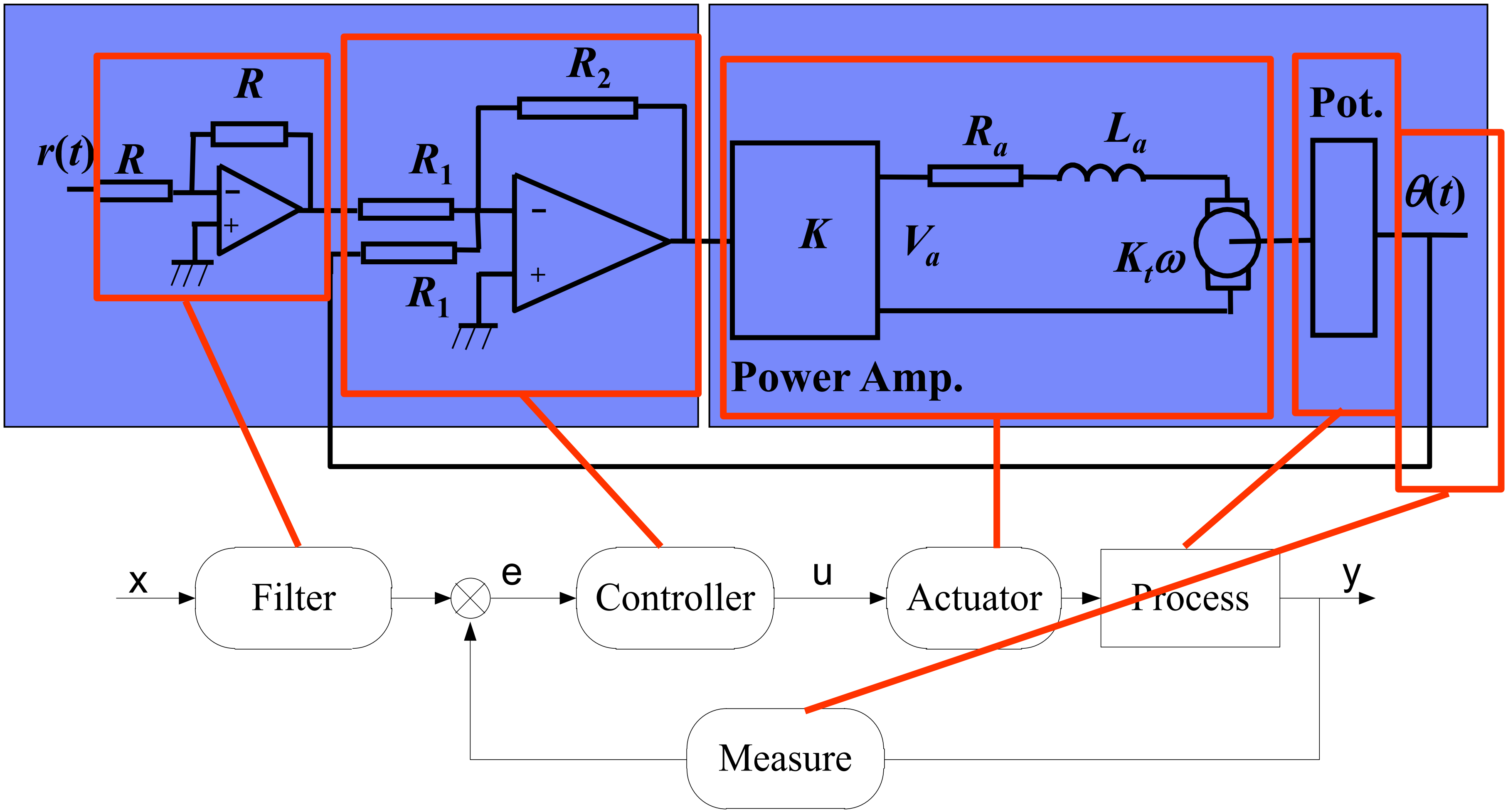
1.2 Introduction to Digital Control Systems

- Analog control system and digital control system

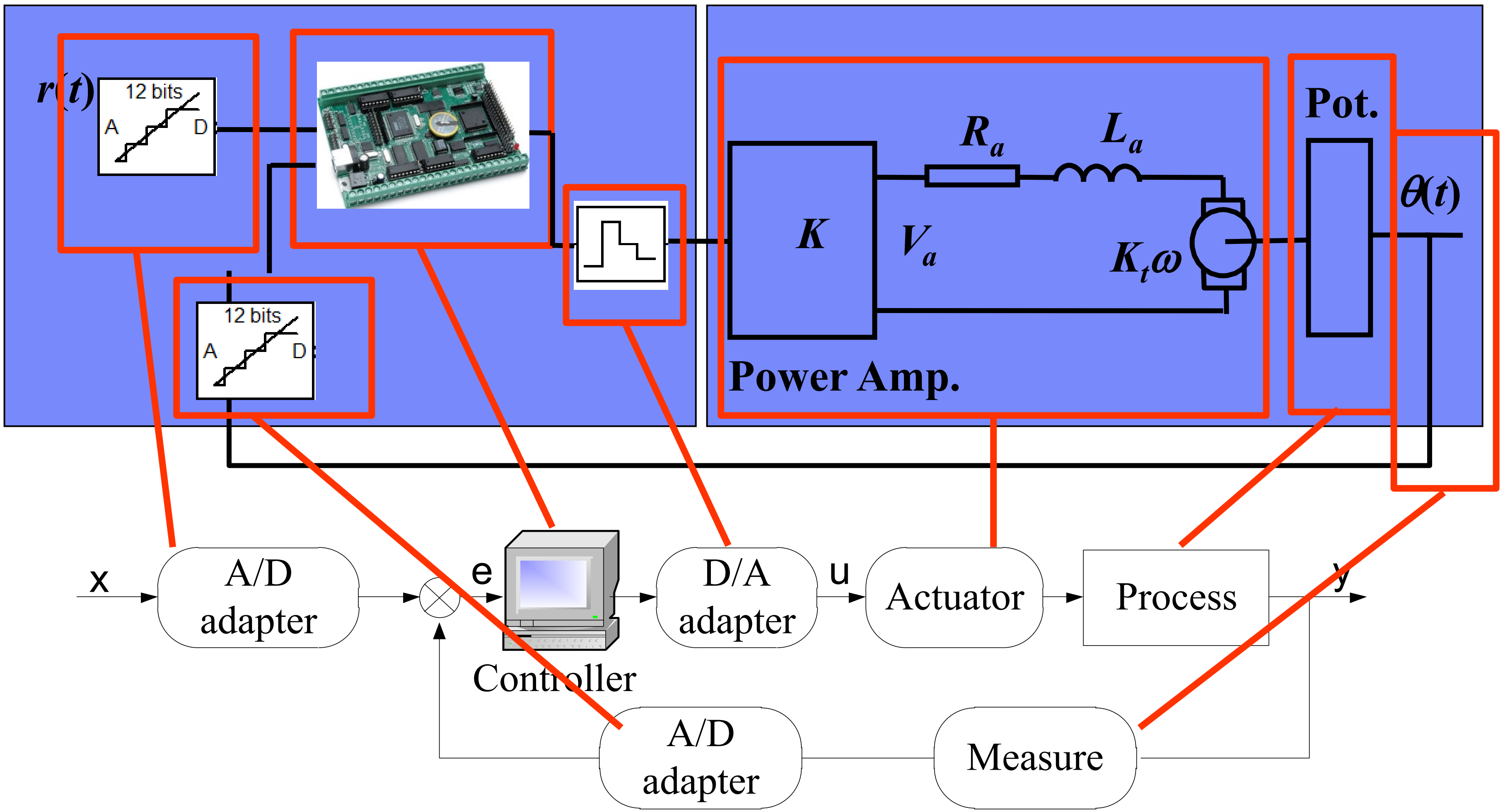
Analog

Digital

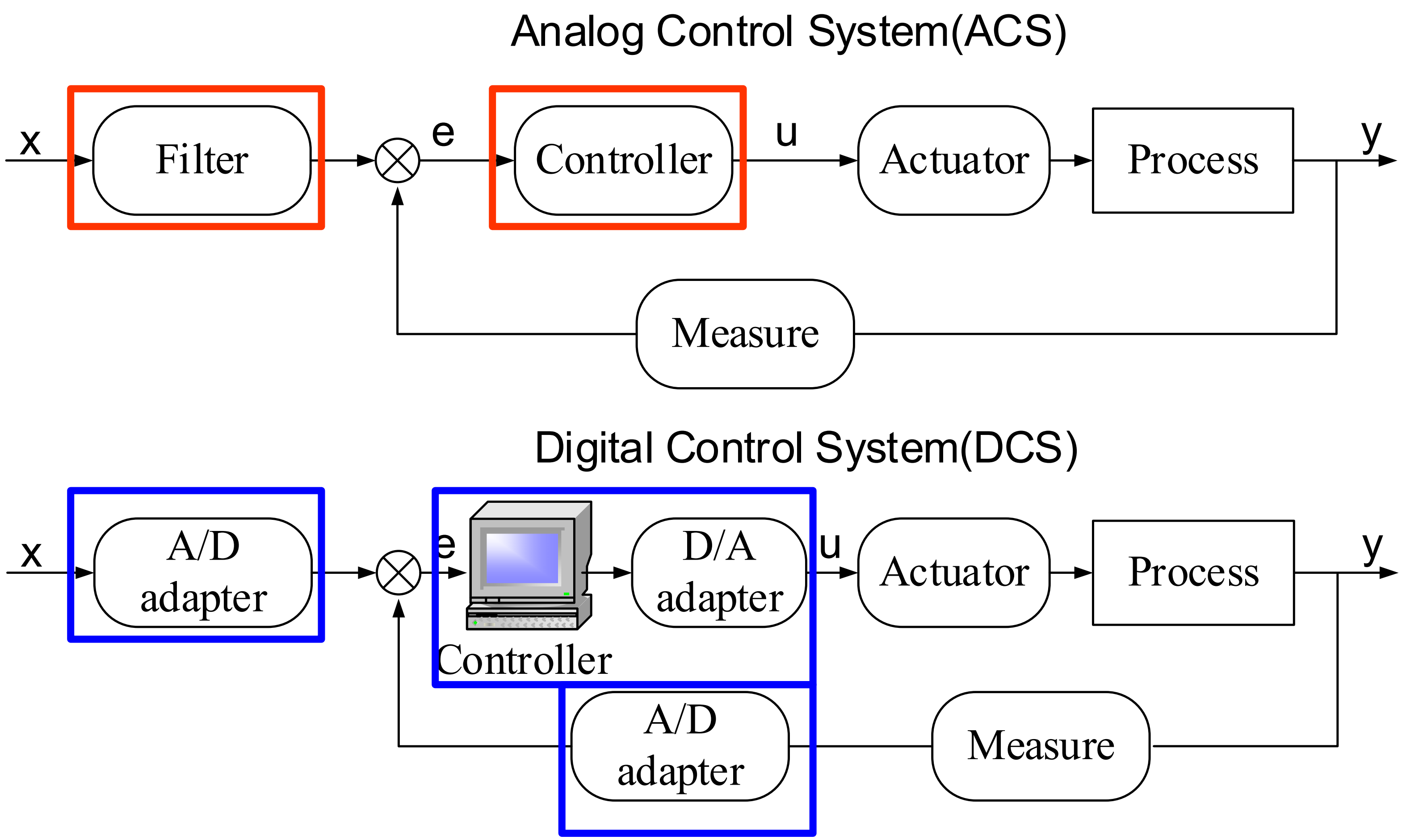
- Analog control system



- Digital control system



- Analog control system and digital control system



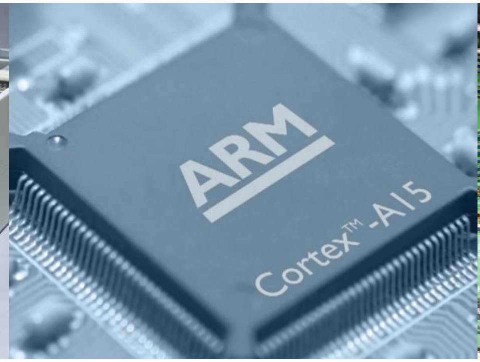
- Comparison between analog and digital control systems

	ACS	DCS
Structure:	Plant Actuator Measure Controller (correcting network)	Plant Actuator Measure Controller (digital computer) Adapter (A/D, D/A)
Components:	Analog	Digital + Analog
Signals:	Analog	Continuous analog Discrete analog Discrete digital

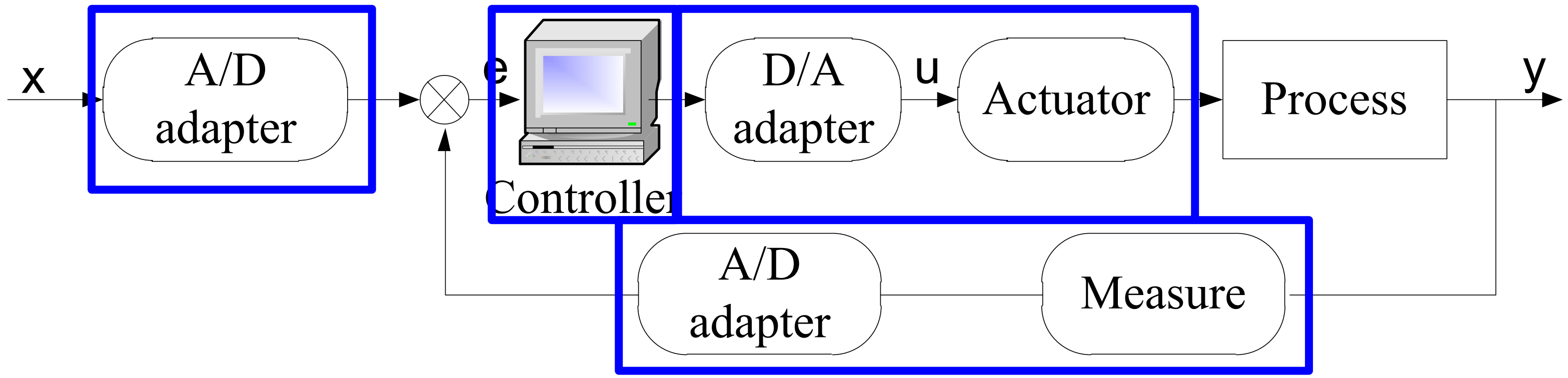
- Virtues
  - Strong computation ability for realizing complex control algorithms
  - High precision: 10^{-70} (analog: 10^{-2})
  - High volume memory: store a great deal of information
  - Robust: use digital components
  - Flexible: control algorithms easily modified
- Defects
  - Lose information during conversions: quantization error
  - Computation delay: especially for serial computation and complex control algorithms

- The role of computer in a digital control system:
  - Compute the control actions
  - Collect data
  - Implement some advance control algorithms, such as optimal control, neural network control, predictive control, etc

- Typical computers used in the digital control system



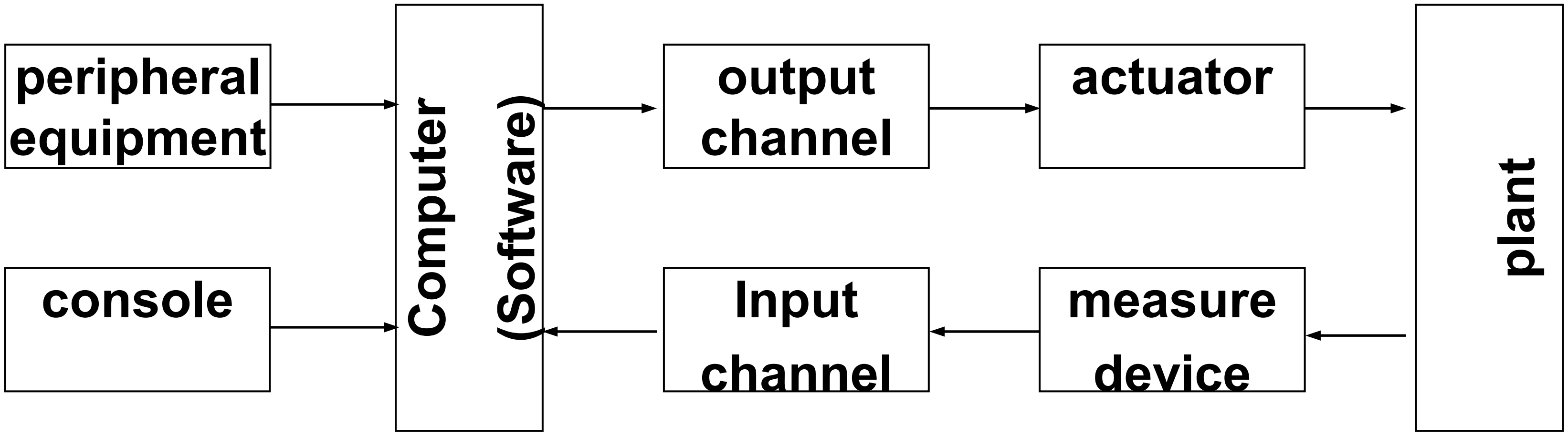
- In each control cycle, the operation of a digital control system can be summarized as three steps:
  - Real time data collection: Measure and collect the states of the plant
  - Real time decision: Compute the control actions based on the reference and measurements
  - Real time implementation: Implement the computed control actions to the plant



- In the next control cycle, these three steps are repeated

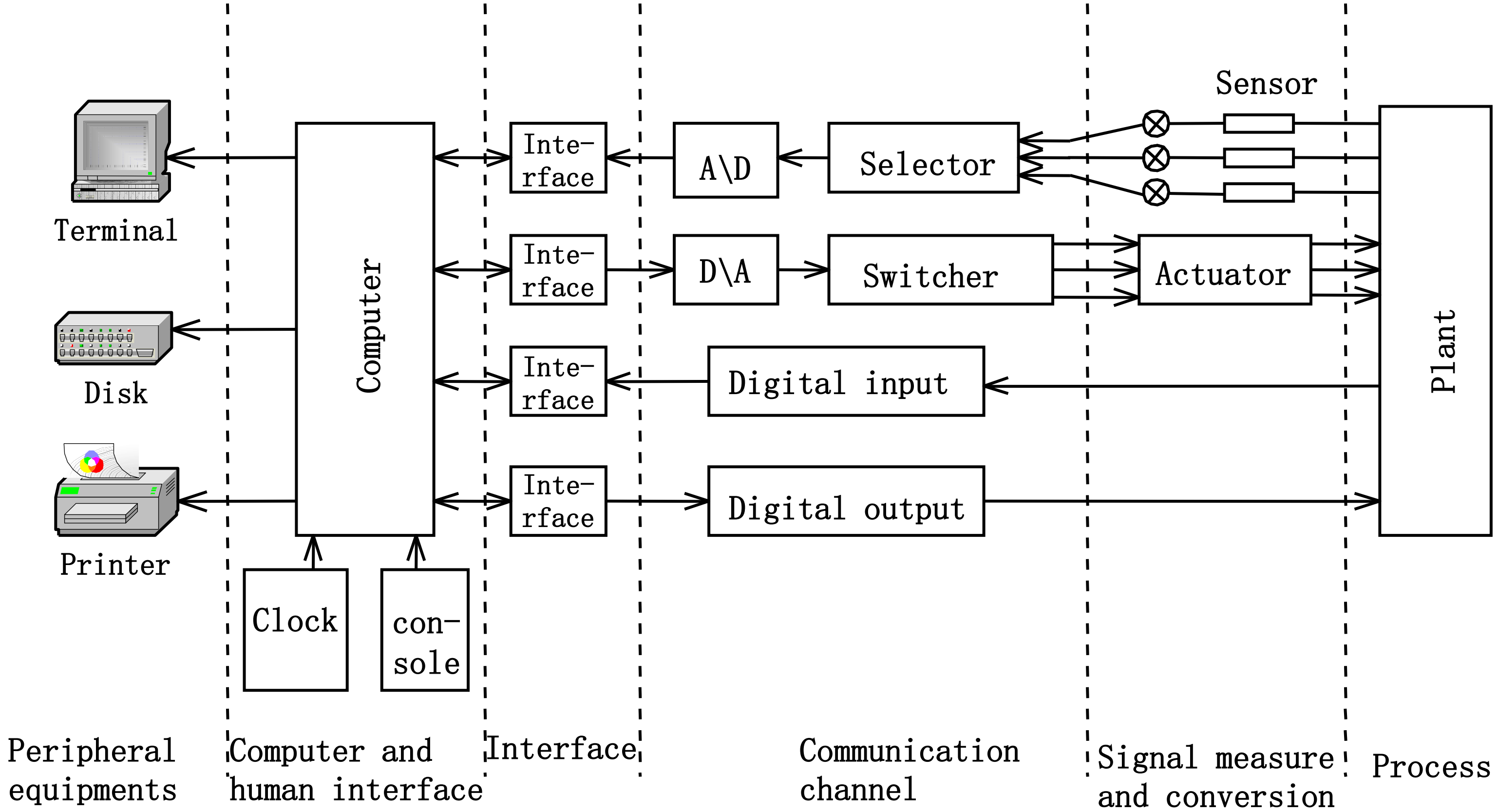
Practical Structure of digital control systems

- In general, a digital control system is constitute of computer, peripheral equipment, console, input and output channels, actuator, measure devices, plant, and software
  - Hardware
  - Software



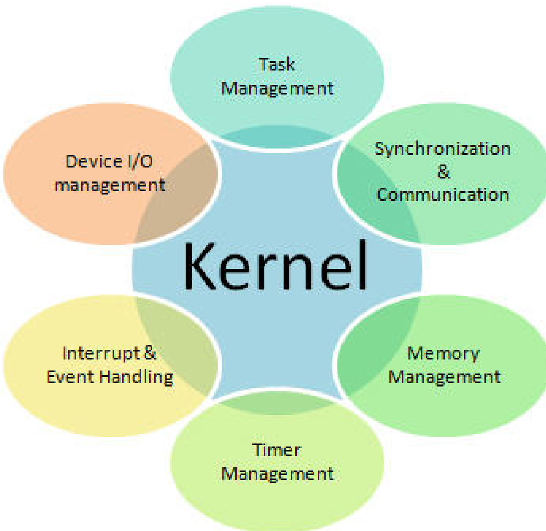
Hardware components

- Hardware components include the computer, human interface, peripheral equipment, input and output channels, and process



Software components

- Soul of a digital control system
  - System software
  - Application software



Software
- System Software
  - Boot loader
  - Operating System
- Application Software
  - Control application program
  - Human interface, display
  - Database, network communication

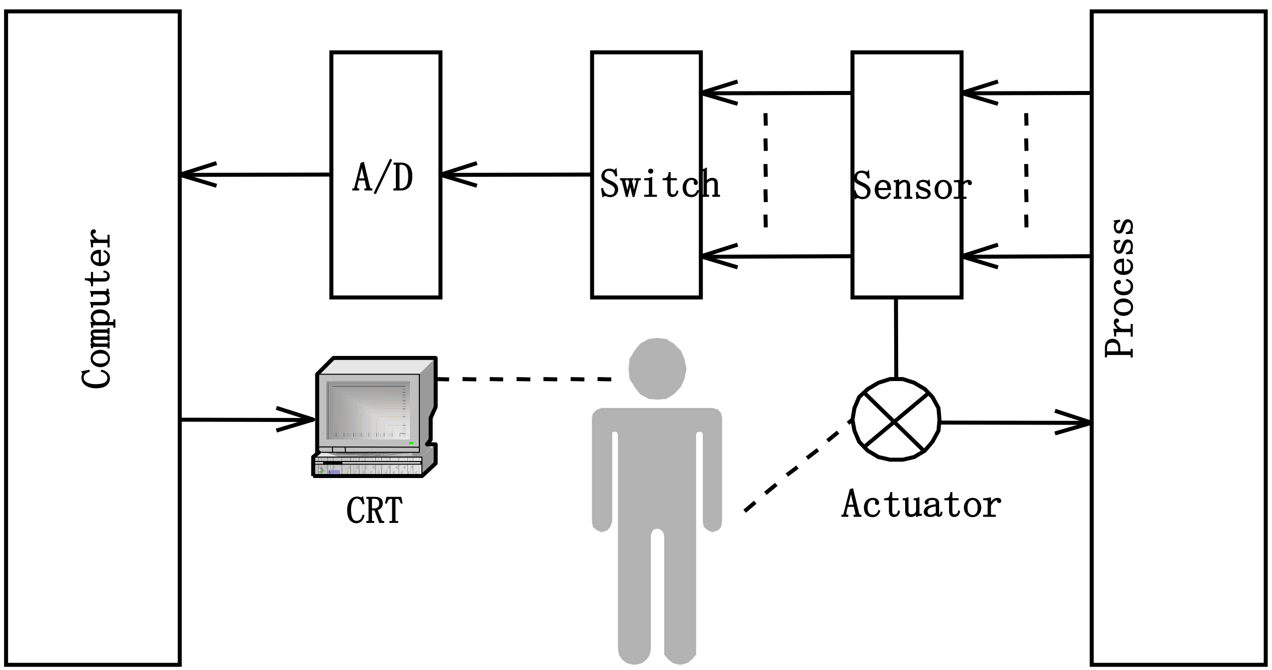
- Simple control applications
  - Boot loader + Interrupt
- Complex control applications
  - uC/OS-II, Windows CE, VxWorks, Embedded Linux

Contents

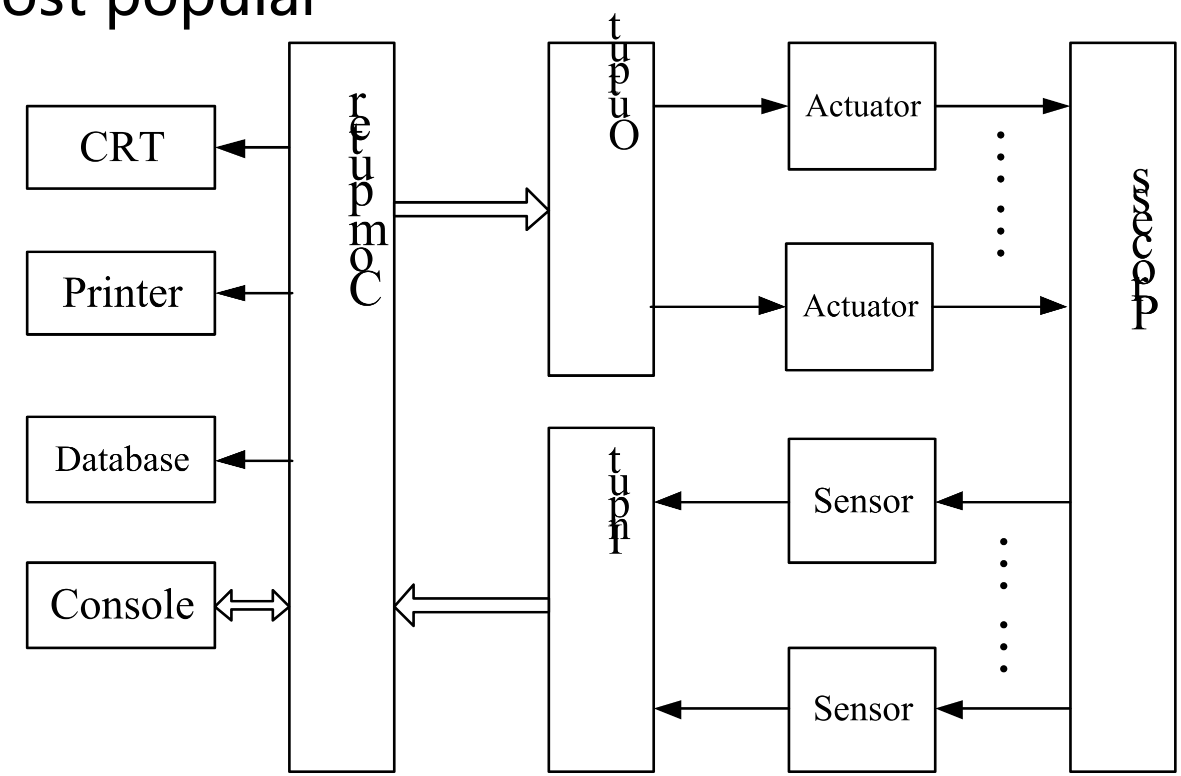
- **1.1 Control problem**
- **1.2 Introduction to digital control systems**
- **1.3 Categories of digital control systems**
- **1.4 digital control theory**

1.3 Categories of digital control systems

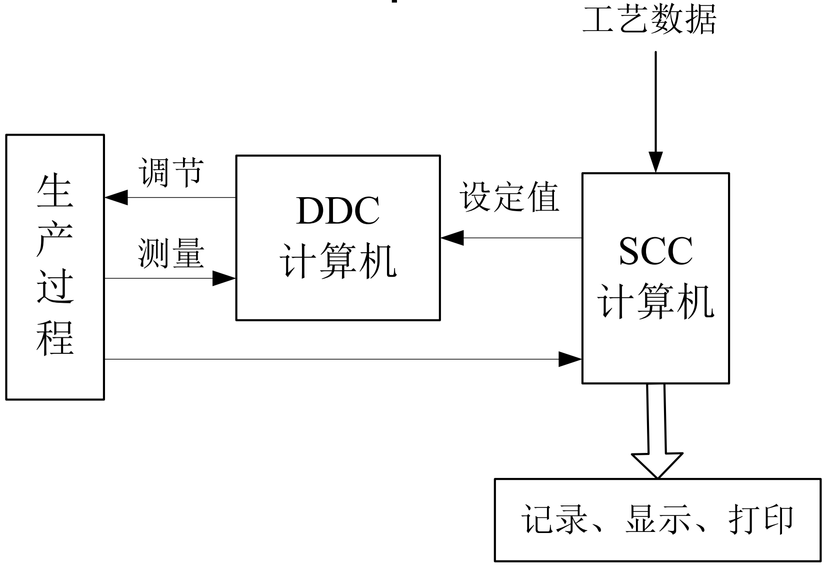
- Operation guide control system
  - Simple, flexible, safe
  - Slow, single channel
  - For design and tuning



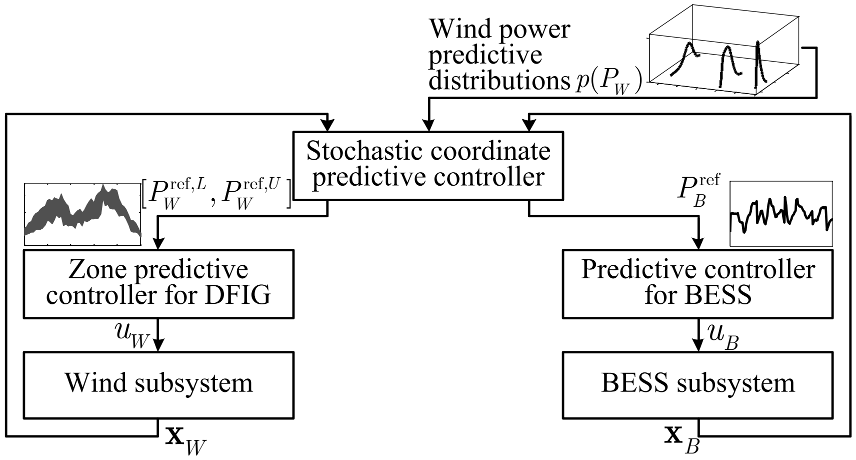
- Direct digital control
  - Close-loop control system
  - Multi-control algorithms
  - Control multi-loops simultaneously
  - Most popular



- Supervisory digital control
  - Upper computer control + lower computer control (analog or digital)
  - Upper computer: high-level control and management for set point control, sequential control and optimal control
  - Lower computer: control the process

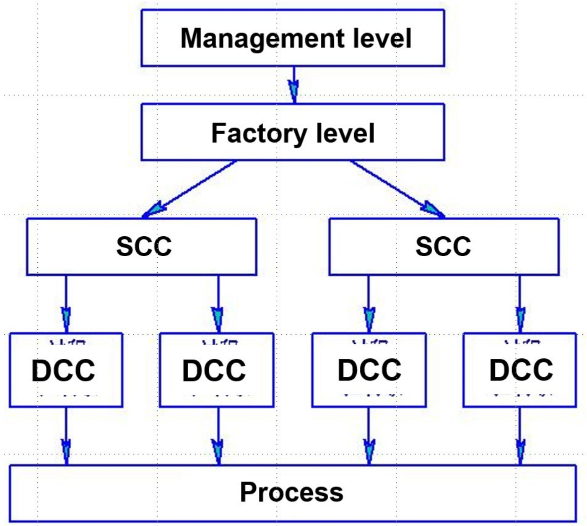


SCC + ACS

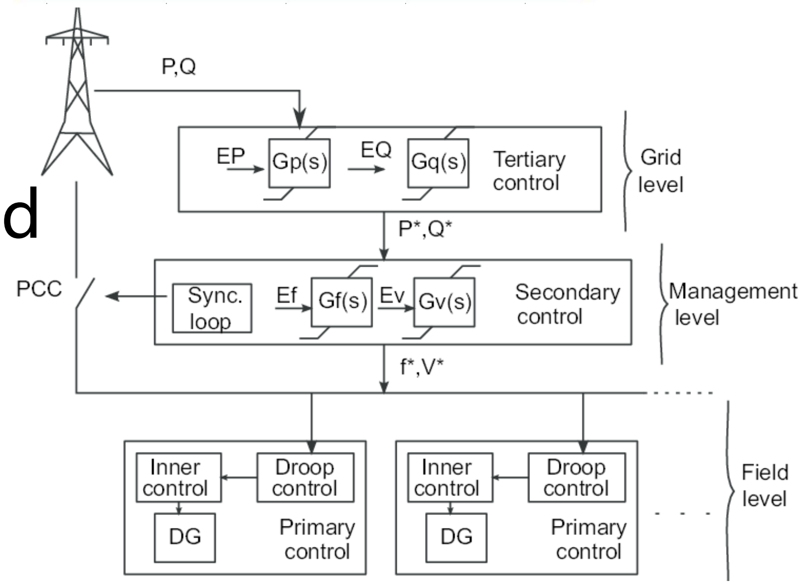


Coordinated control of WBHS

Hierarchical control system

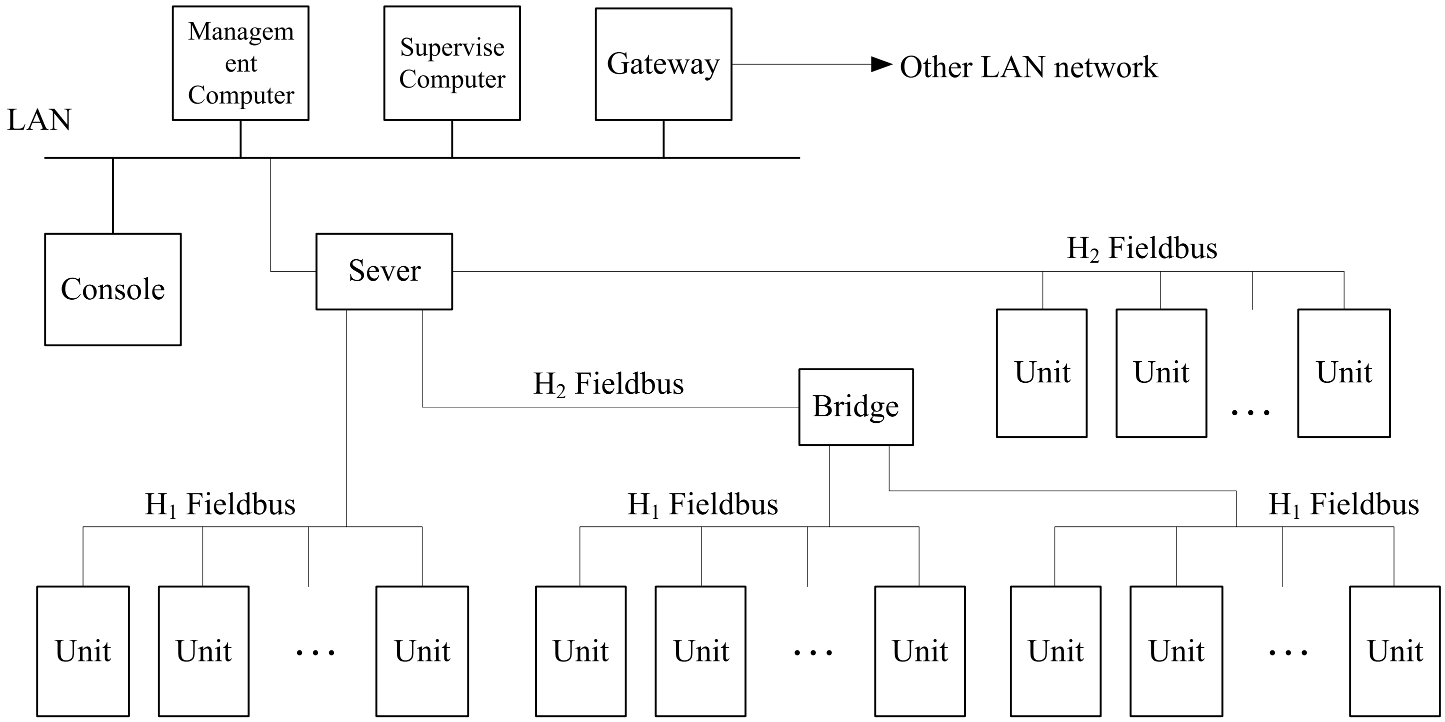


Microgrid control



- DCC: for process
- SCC: coordinate and supervise DCCs for shop' s optimal control
- Factory level: make plan for the factory and report the data of SCCs and DCCS
- Management level: make long-term plan, coordinate the full company and global optimization

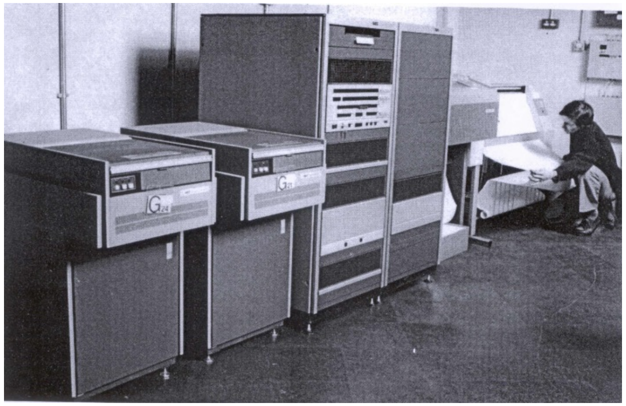
- Fieldbus control system
  - Communication technologies and products used in automation and process control industries
  - Reduces the complexity of the control system in terms of hardware outlay



History of digital control

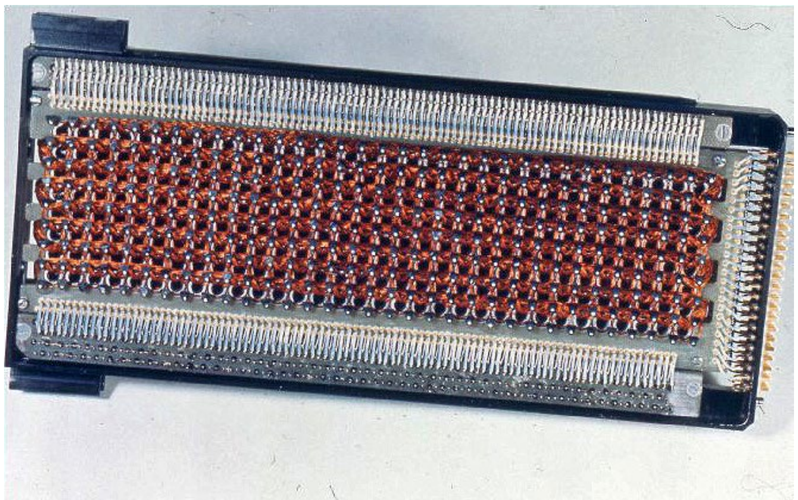
- 1952-1965: pioneering period
  - Thomson Ramo Woodridge and Texaco: a computer-controlled system for the polymerization unit in a refinery factory in Texas was designed

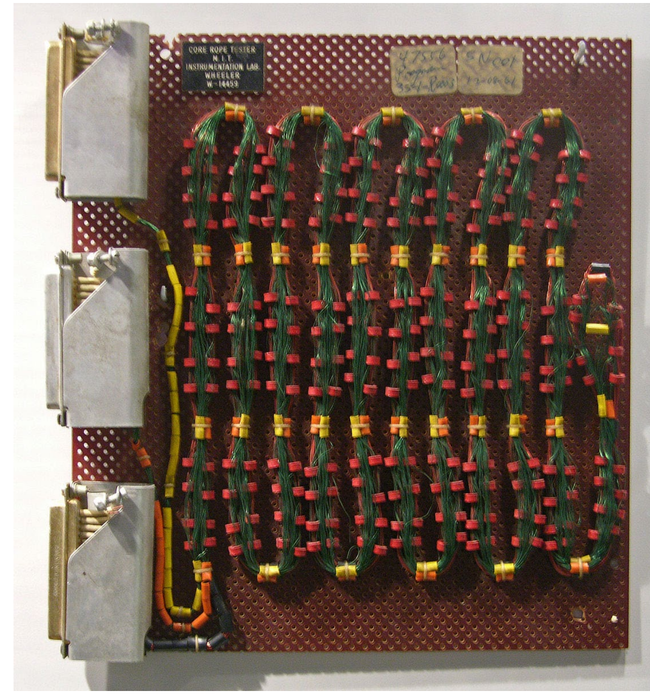
- 1965-1972: industry application period
  - Minicomputer
  - Computer central control

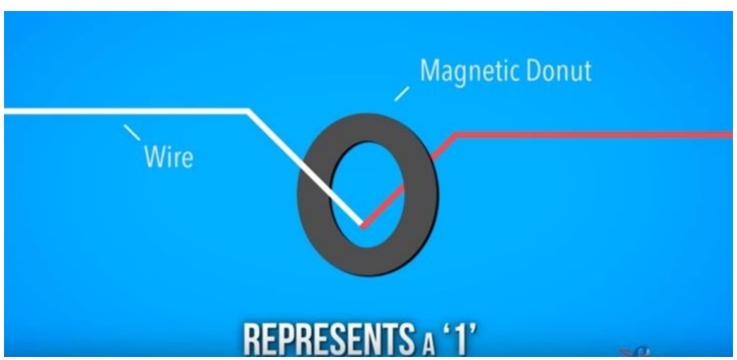


Core rope memory

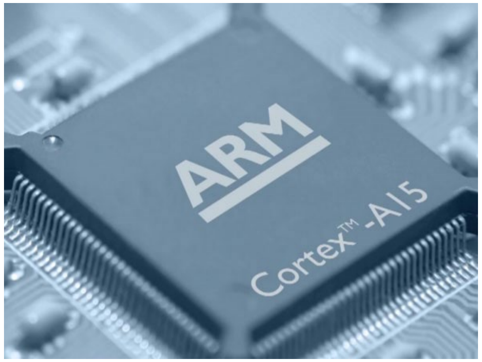
- Used in Apollo program (1960-1972)
- Textile worker

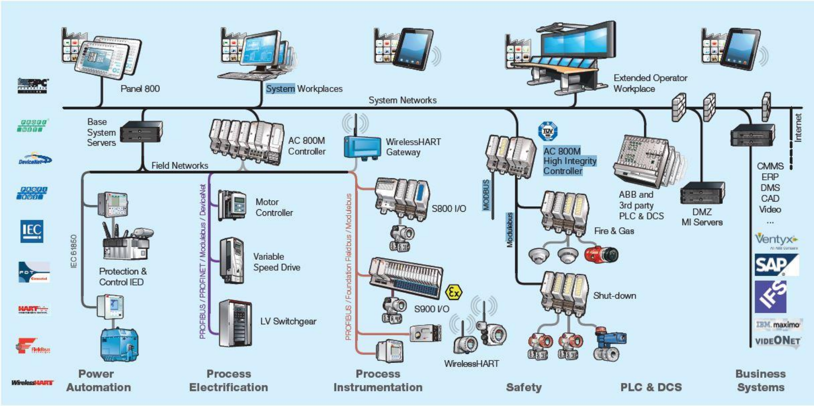




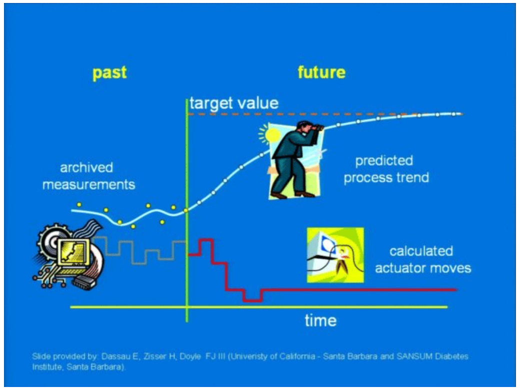


- 1972-: development period
  - Microcomputer period and general use of computer control
  - PLC (Programmable logic controller)
  - Distributed control system
  - Embedded system
  - Network control system
  - Fieldbus system





- The future of the technology related to DCS
  - Process knowledge
    - Continuous increasing process knowledge
    - System learning
  - Measurement technology
    - Data merging
    - Soft measurement
  - Computer technology
    - Computation ability, visualization, communication
    - Programming (Code generation)
  - Control theory
    - Model predictive control, adaptive control
    - More complex control algorithm
    - Data-driven modeling and control



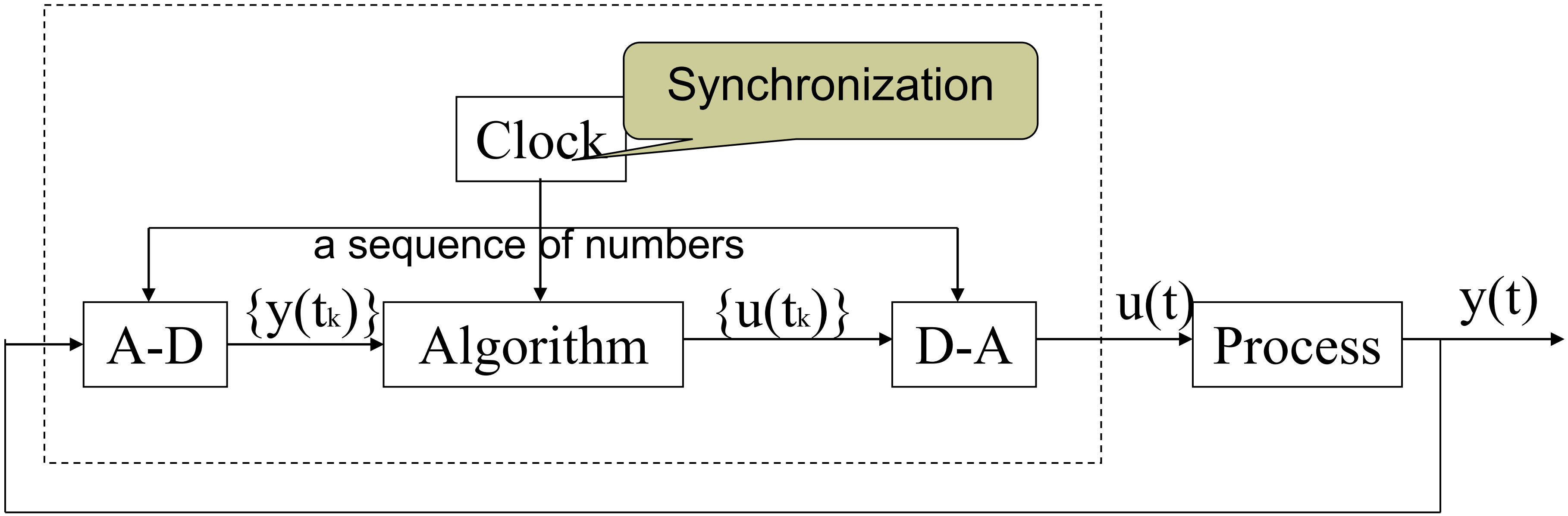
Contents

1.4 Digital control theory

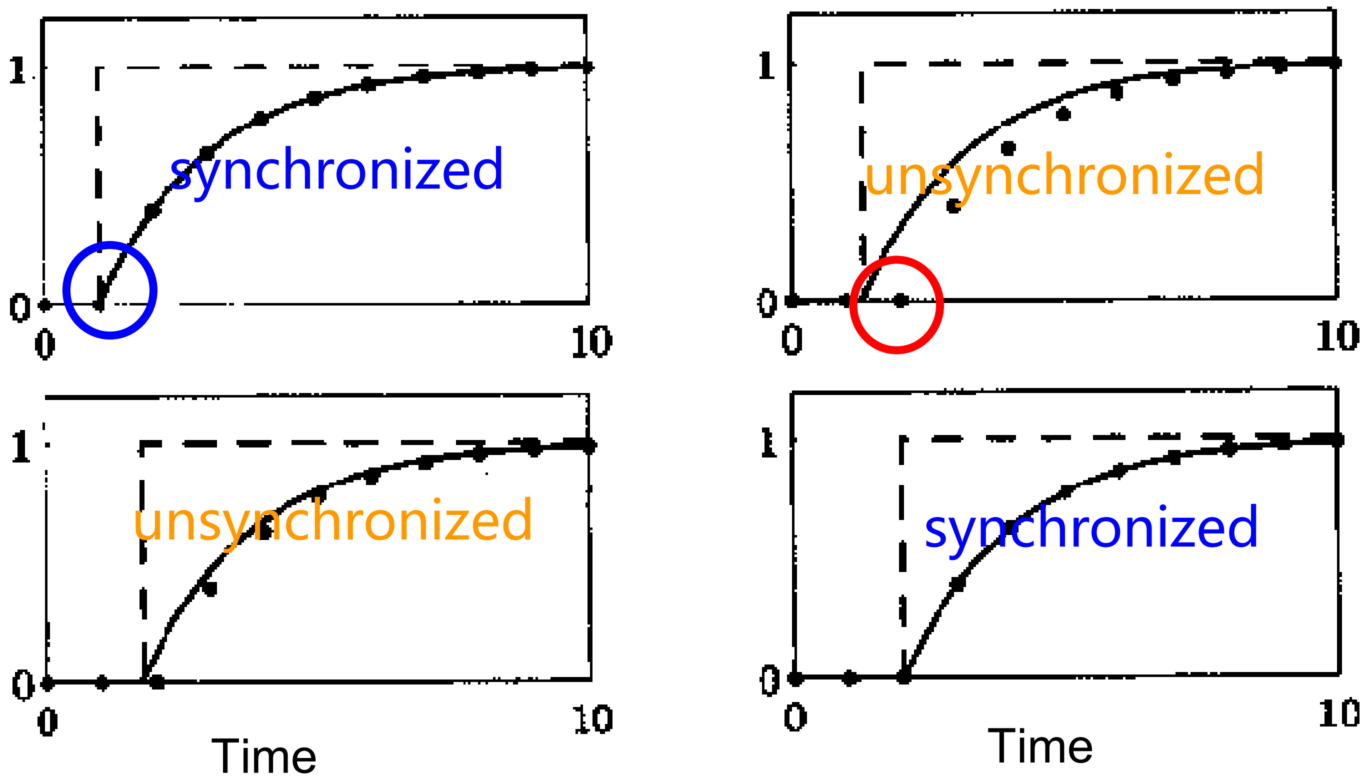
- Digital control system has its own particular characteristics
- The theory of analog control system cannot be applied directly

Synchronize

Example Time dependence in digital controller



- Synchronized and unsynchronized systems



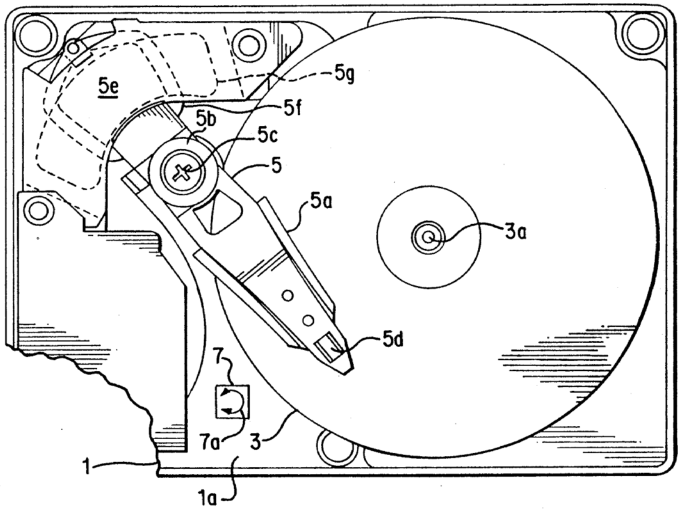
- Phenomena:
  - The figure clearly shows that the sampled system is not time-invariant because the response depends on the time when the step occurs.

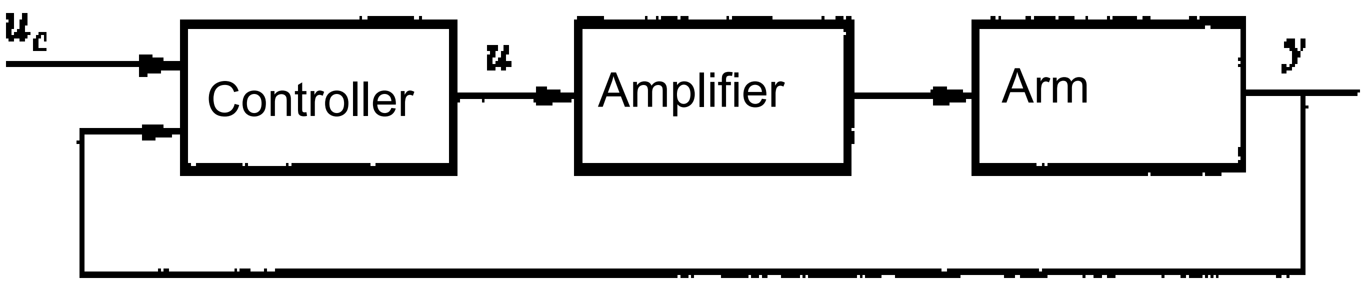
- Summary:
  - The response of the system to an external stimulus will then depend on how the external event is synchronized with the internal clock of the computer system.

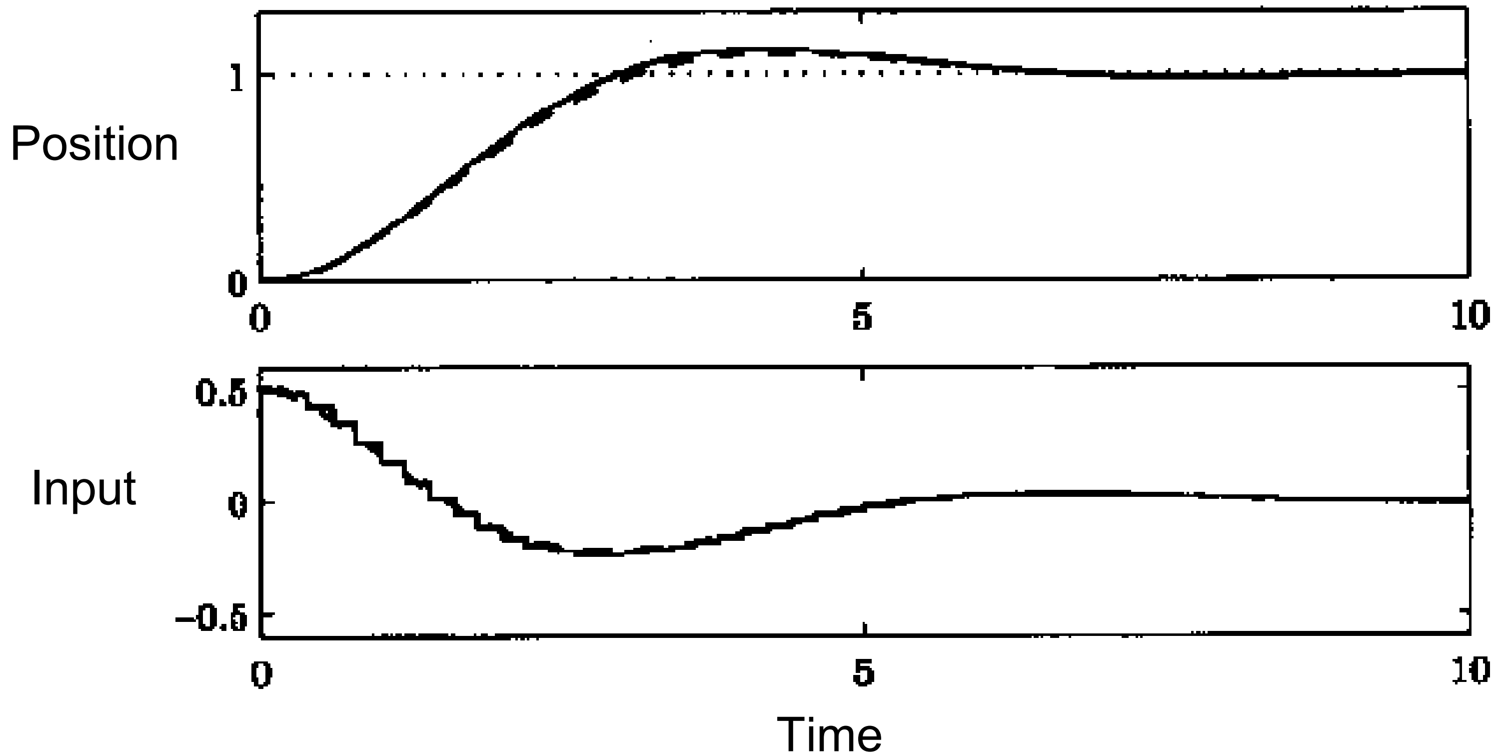
Sampling interval

A naive approach to DCS

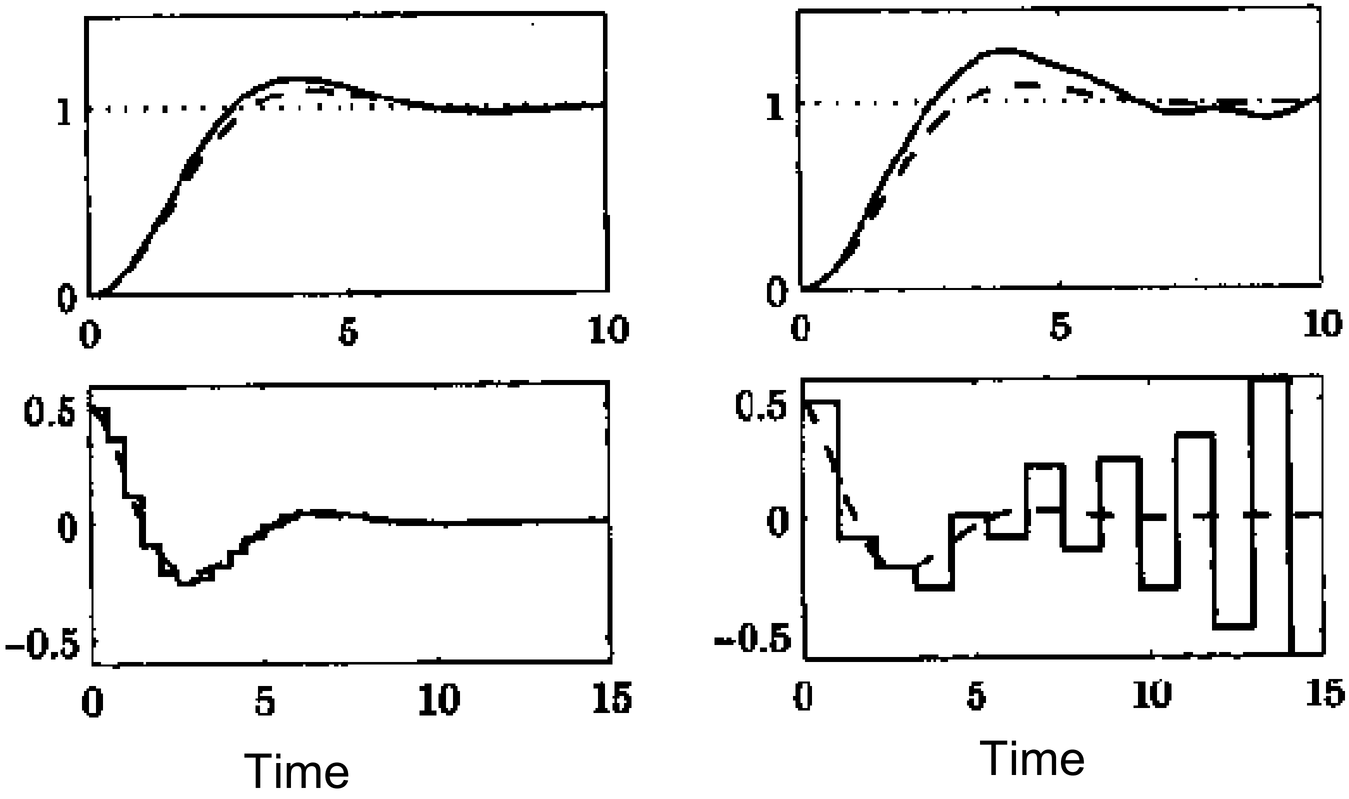
Controlling the arm of a disk drive







Control inputs and performance of ACS and DCS



Control performance of DCS with different sampling intervals

- **Phenomena:**
  - When sampling period is very small, the difference between the outputs of the systems is very small.
  - When the sampling period getting longer, the performance of DCS will deteriorate.

- **Summary:**
  - The performance and stability of DCS are highly dependent on the sampling interval.

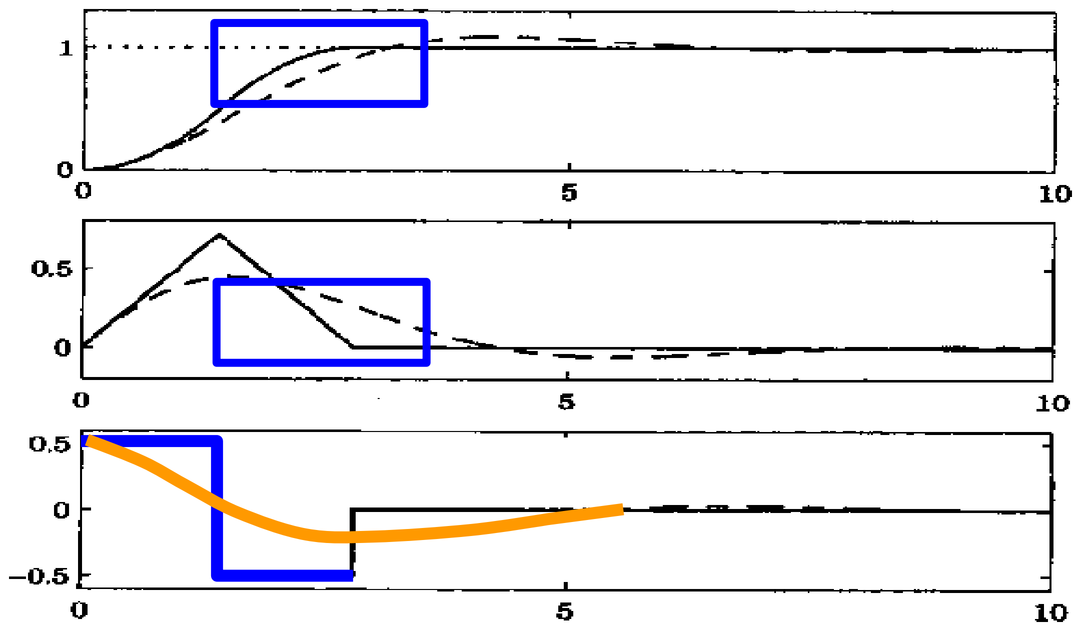
Deadbeat control

Disk drive with deadbeat control

Position

Speed

Control signal



Time

Position control using the deadbeat control method

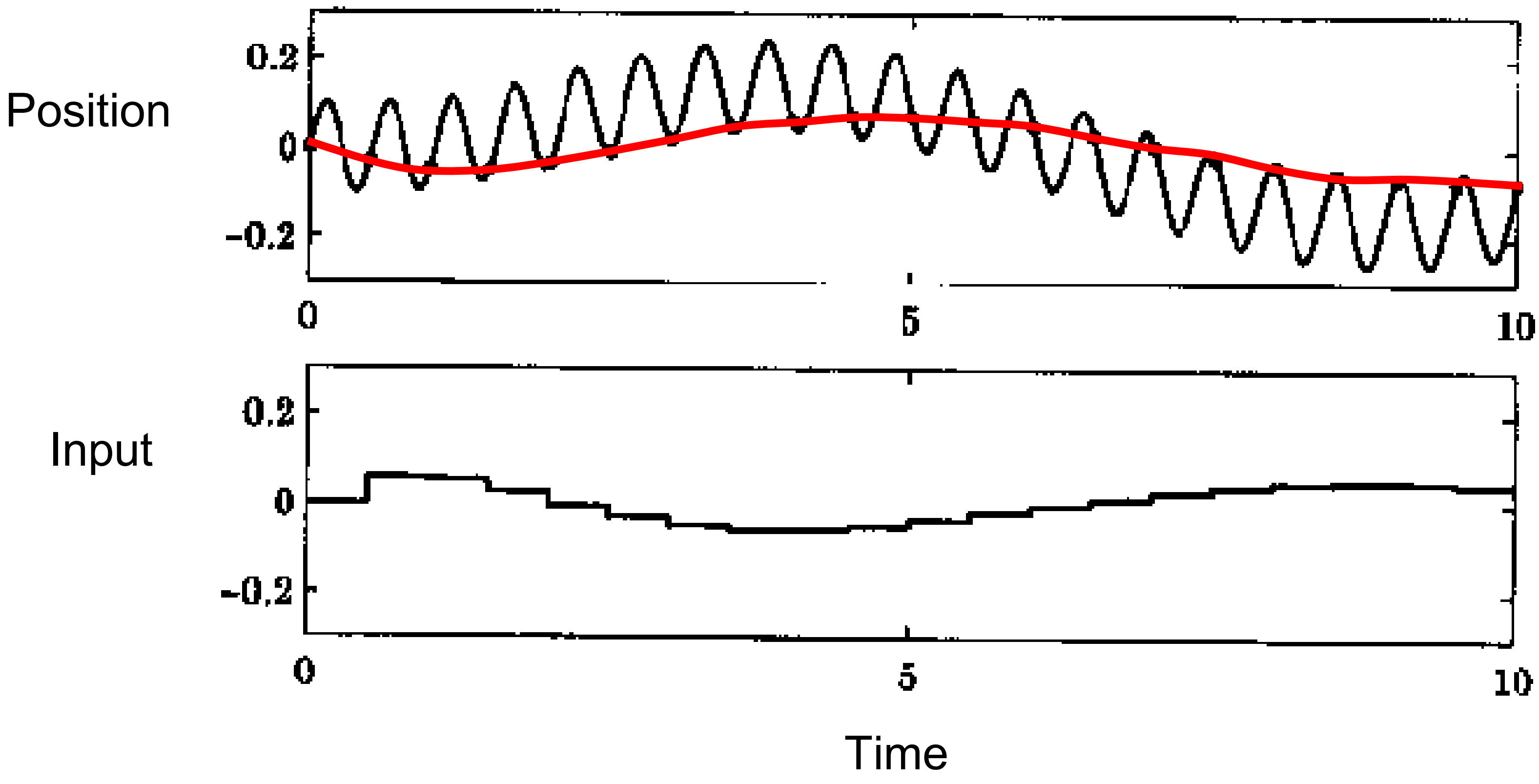
- Phenomena:
  - The excellent behavior of the DCS.
  - This behavior cannot be obtained with continuous-time system.
- Summary:
  - This kind of control strategy is called deadbeat control because the system is at rest when the desired position is reached. Such a control scheme, as well as some other advance control schemes, cannot be obtained with a ACS.

Aliasing

- Aliasing: The phenomenon that the sampling process creates new frequency components.
- Sampling of a signal with frequency ω creates signal components with frequencies

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

where ω_s is the sampling frequency, and n is an arbitrary integer.


Position
0.2
0
-0.2
0
5
10
Input
0.2
0
-0.2
0
5
10
Time

- Phenomena:
  - Sampling creates new frequencies.
  - Information distortion.

- Summary:
  - There will be low-frequency components created whenever the sampled signal contains frequencies are larger than half the sampling frequency.

- Presampling filters or antialiasing filters
  - Nyquist frequency: half of sampling frequency
  - To avoid the above difficulties, it is essential that all signal components with frequencies higher than the Nyquist frequency are removed before a signal is sampled.
  - The filters that reduce the high-frequency components of the signals are called antialiasing filter.
  - These filters are an important component of DCS.
  - The proper selection of sampling periods and antialiasing filters are important aspects of the design of DCS.

Conclusion

- DCS has particular characteristics.
- DCS have the potential of giving control schemes with behavior that cannot be obtained by ACS.
- Sampling operation leads to some phenomena that are not found in ACS systems (e.g., aliasing).
- The selection of the sampling period is important and it is necessary to use anti-aliasing filters.
- All show that DCS cannot be fully understood within ACS framework, it is thus useful to have other tools for analysis.

Call for the theory of digital control

How theory developed

- The Sampling Theorem
- Difference Equation
- Numerical Analysis
- Transform Methods
- State-Space Theory
- Optimal and Stochastic Control
- System Identification
- Adaptive Control
- Automatic Tuning

Main contents of this course

- Goal: Understand, analyze and design computer-controlled systems
  - Sampling and reconstruction
  - Description of computer-controlled systems
  - Analysis
  - Indirect design
  - Direct design