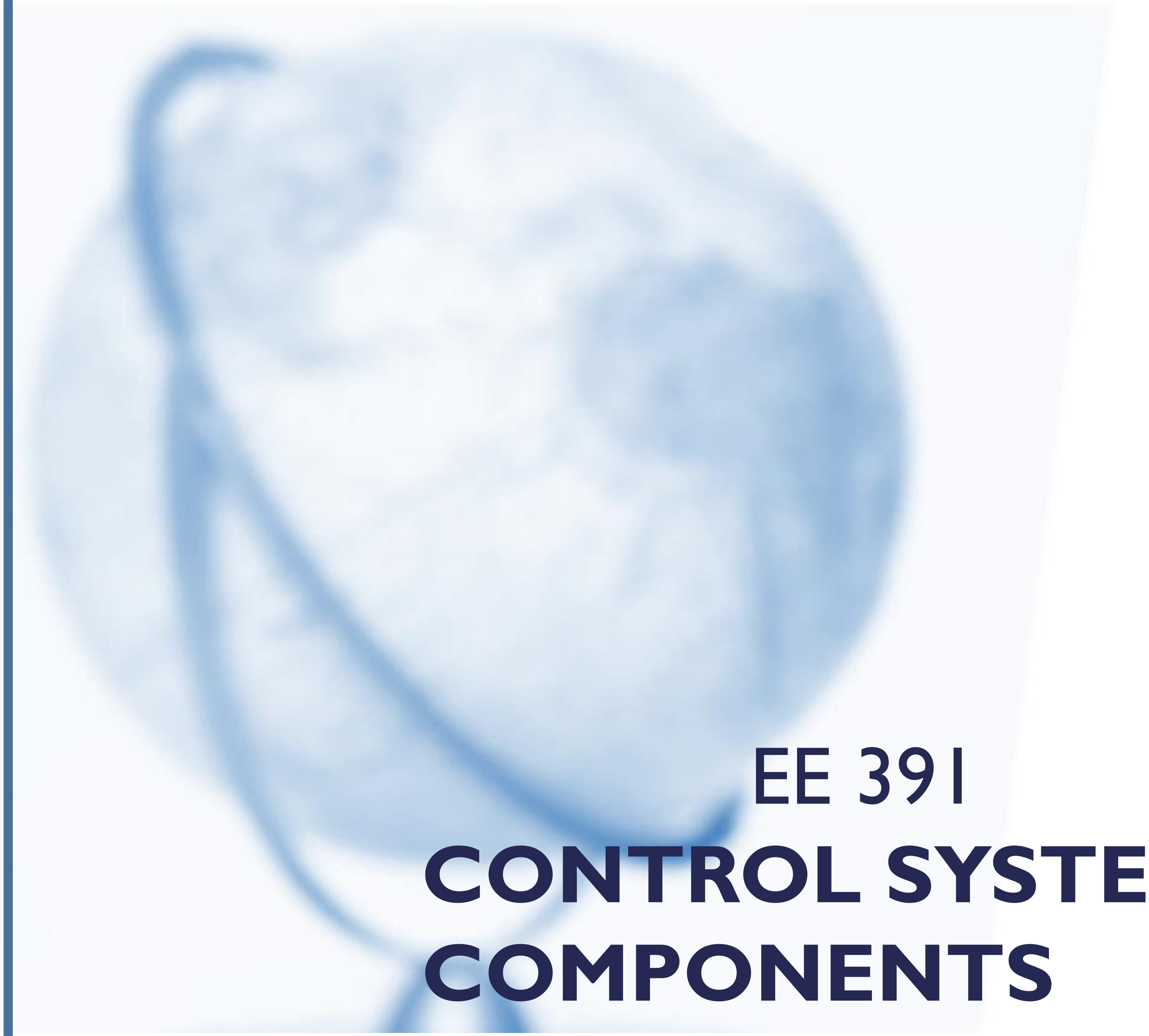

EE 391

CONTROL SYSTEMS AND COMPONENTS

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Course Staff

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- Office hours :
  - Wednesday 1:30-3:00PM
  - Thursday 10:00-11:30AM

Basic Info.

- Textbook
  - “Modern Control Engineering”, Katsuhiko Ogata
- Supplementary References
  - “Modern Control Systems”, Richard Dorf, Robert Bishop
  - “Automatic Control Systems”, Benjamin C. Kuo & F. Golnaraghi
  - “Control Systems Engineering”, Norman Nise

Basic Info. (2)

- Computer tool: MATLAB with control toolbox
  - a high-level language and interactive environment
  - enables you to perform computationally intensive tasks faster than C, C++, and Fortran
  - a powerful tool for control system designers

Course Objectives

- After the completion of this course you should be able to:
  - Define a control system and describe a control system's design process
  - Understand the basic concepts and disciplines of automatic control
  - Model electrical and mechanical systems in the time and frequency domains
  - Analyze and design feedback control systems using both classical and modern techniques
  - Use Matlab to analyze and design control systems

Course Outline

- Introduction to control systems
- Mathematical modeling of control systems
- Time-domain analysis of control systems
- The root-locus method
- Frequency-domain analysis
- State-space methods

Course Work

- 6 Labs
- 2 Projects
- A Midterm exam
- A Final Exam
- Tools:
  - Matlab and Simulink toolbox

Grading

- Steady and persistent effort is rewarded
  - Labs: 30 marks
    - Attendance: 6 marks
    - Lab work: 12 marks
    - Projects: 12 marks
  - Midterm exam: 30 marks
  - Final exam: 90 marks

Chapter 1

Introduction to Control Systems

Outline

- ☐ Introduction
- ☐ Historical review
- ☐ Examples of Control Systems
- ☐ Control system components
- ☐ Open-loop control versus closed-loop control
- ☐ Classification of control systems
- ☐ Design procedures of control systems

Introduction

- Automatic control is essential in any field of engineering and science
- Automatic control is an important and integral part of space-vehicle systems, robotic systems, modern manufacturing systems, and any industrial operations involving control of temperature, pressure, humidity, flow, etc

Introduction (2)

- Generally speaking, a control system is a system that is used to realize a desired output or objective.
- Control systems are everywhere
  - **They appear in our homes, in cars, in industry, in scientific labs, and in hospital…**
  - **Principles of control have an impact on diverse fields as engineering, aeronautics ,economics, biology and medicine…**
  - **Wide applicability of control has many advantages (e.g., it is a good vehicle for technology transfer)**

Historical Review

- Birth of mathematical control theory
  - G. B. Airy (1840)
    - the first one to discuss instability in a feedback control system
    - the first to analyze such a system using differential equations
  - J. C. Maxwell (1868)
    - the first systematic study of the stability of feedback control
  - E. J. Routh (1877)
    - deriving stability criterion for linear systems
  - A. M. Lyapunov (1892)
    - deriving stability criterion that can be applied to both linear and nonlinear differential equations
    - results not introduced in control literature until about 1958

Historical Review (2)

- Birth of classical control design method
  - H. Nyquist (1932)
    - developed a relatively simple procedure to determine stability from a graphical plot of the loop-frequency response.
  - H. W. Bode (1945)
    - frequency-response method
  - W. R. Evans (1948)
    - root-locus method

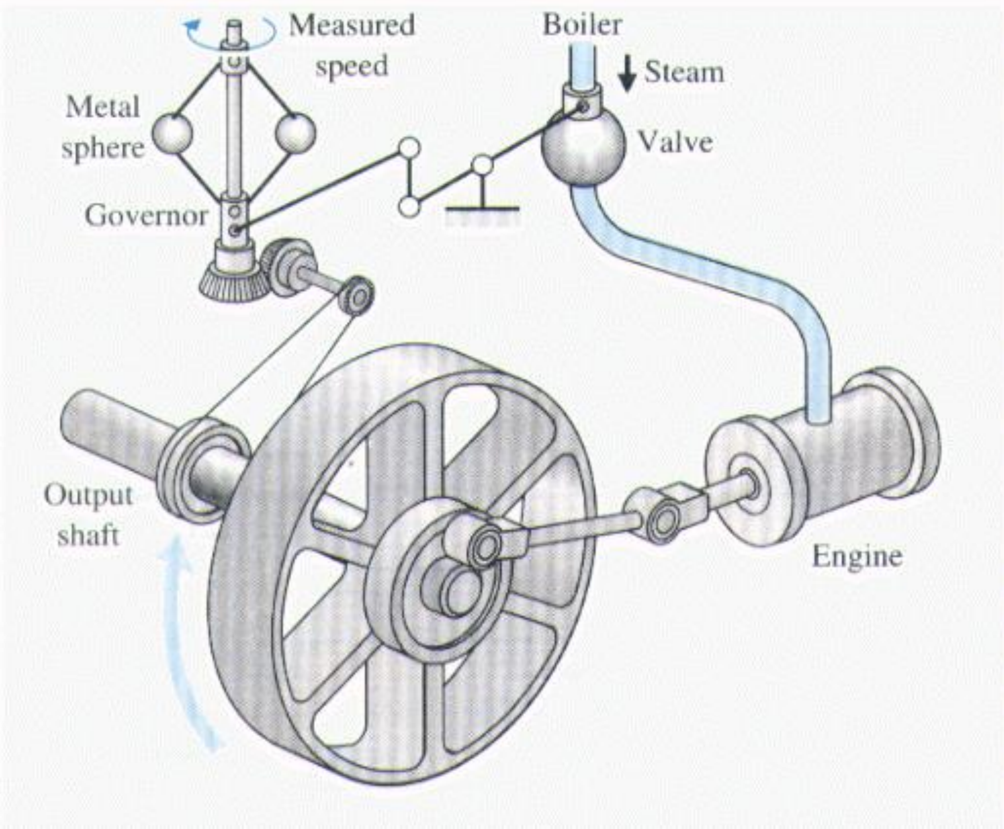
With the above methods, we can design control systems that are stable, acceptable but not optimal in any meaningful sense.

Historical Review (3)

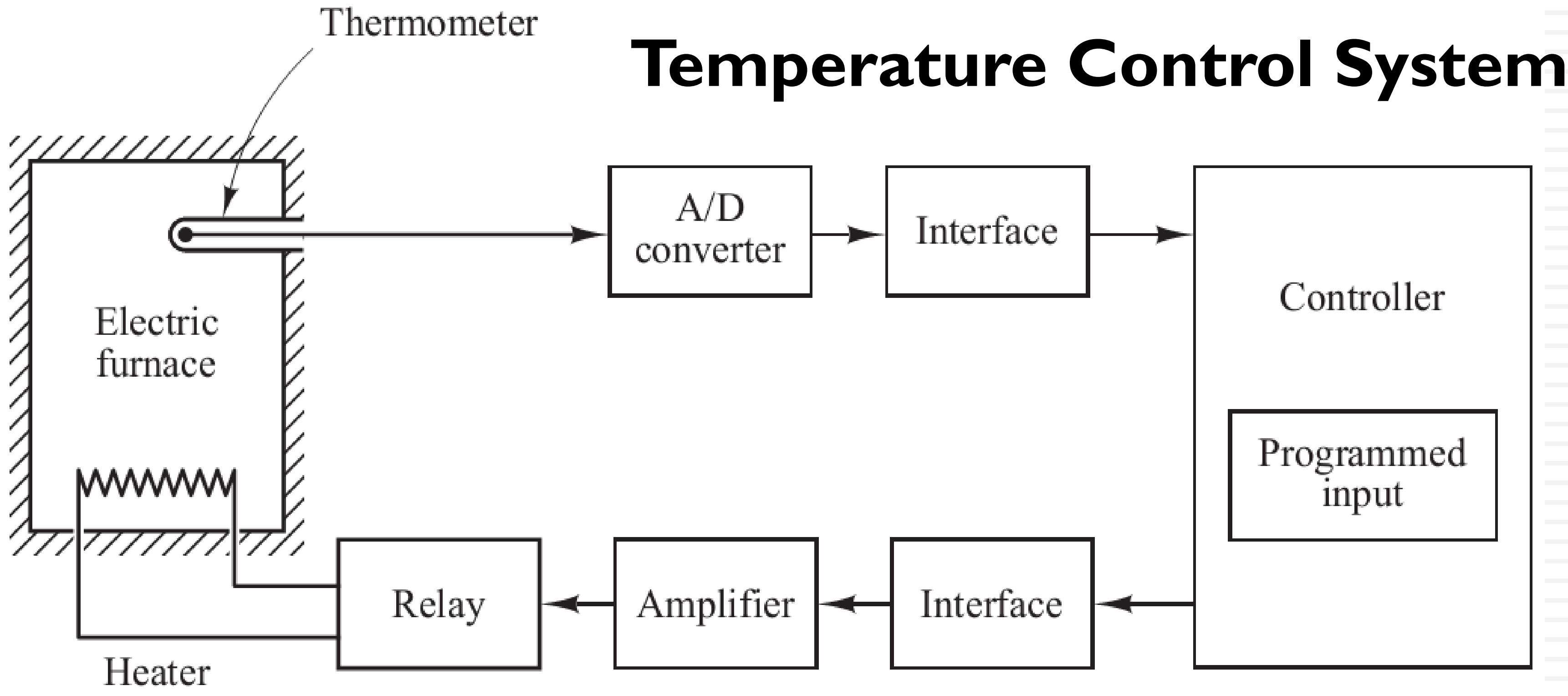
- Development of modern control design
  - Late 1950s: designing optimal systems in some meaningful sense
  - 1960s: digital computers help time-domain analysis of complex systems, modern control theory has been developed to cope with the increased complexity of modern plants
  - 1960s~1980s: optimal control of both deterministic and stochastic systems; adaptive control and learning control
  - 1980s~present: robust control, H-inf control…

Examples of Control Systems

- the first modern controller
- Watt's fly-ball speed governor for a steam engine
- The amount of fuel admitted to the engine is adjusted according to the difference between the desired and the actual engine speed



Examples of Control Systems (2)



Basic Components of Control Systems

- Plant
- Controlled Variable
- Expected Value
- Controller
- Actuator
- Sensor
- Disturbance

Basic Components of Control Systems (2)

Plant

1.Plant: a physical object to be controlled such as a mechanical device, a heating furnace, a chemical reactor or a spacecraft.

Controlled variable

2.Controlled variable: the variable controlled by Automatic Control System , generally refers to the system output.

Expected value

3.Expected value : the desired value of controlled variable based on requirement, often it is used as the reference input

Controller

4.Controller: an agent that can calculate the required control signal.

Actuator

5.Actuator: a mechanical device that takes energy, usually created by air, electricity, or liquid, and converts that into some kind of motion.

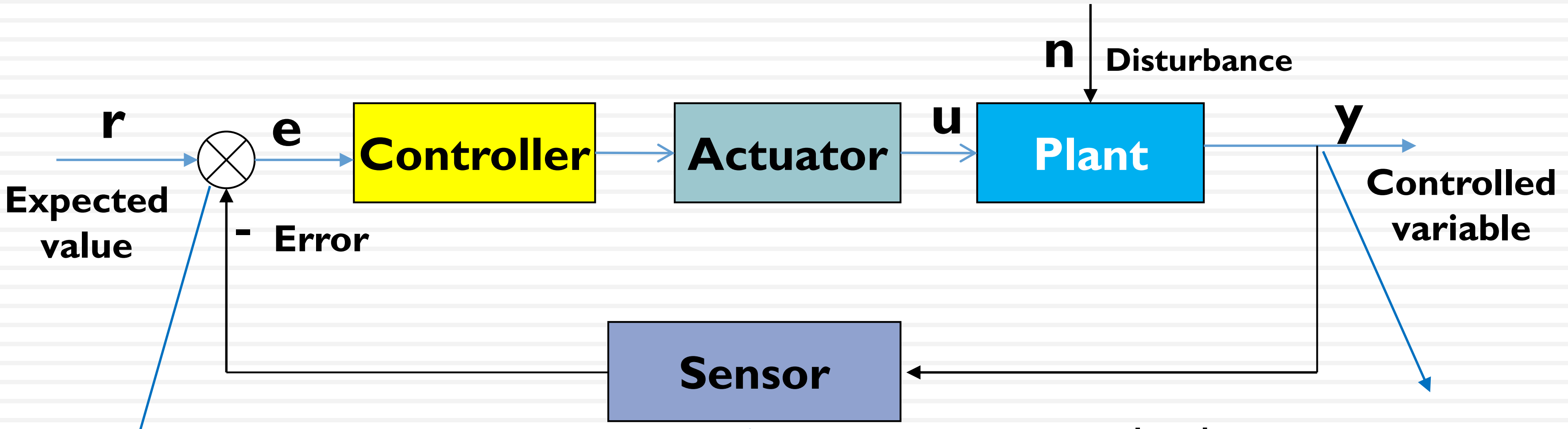
Sensor

6.Sensor : a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument.

Disturbance

7.Disturbance: the unexpected factors disturbing the normal functional relationship between the controlling and controlled parameter variations.

Block Diagram of a Control Systems



comparison component (comparison point) : its output equals the algebraic sum of all input signals.

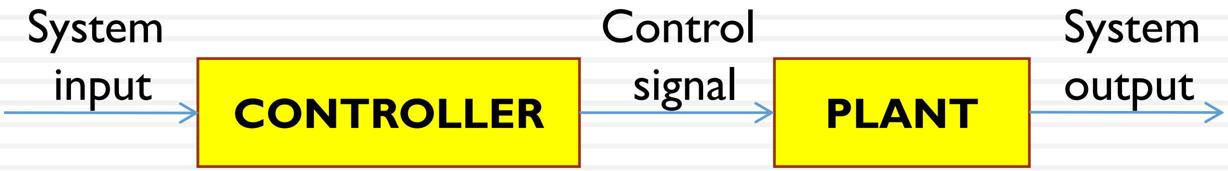
“+”: plus; “-”: minus

The Block represents the function and name of its corresponding mode, we don’t need to draw detailed structure, and the line guides for the transfer route.

lead-out point: Here, the signal is transferred along two separate routes.

Open-Loop Control systems

- Open-loop control systems: those systems in which the output has no effect on the control action.



- The output is neither measured nor fed back for comparison with the input.
- For each reference input, there corresponds a fixed operating conditions; the accuracy of the system depends on *calibration*.
- In the presence of *disturbances,* an open-loop system will not perform the desired task.

Open-loop Control Systems (2)

- Examples
  - Washing machine

  - Traffic signals

Note that any control systems that operates on a time basis are open-loop

Open-loop Control Systems (3)

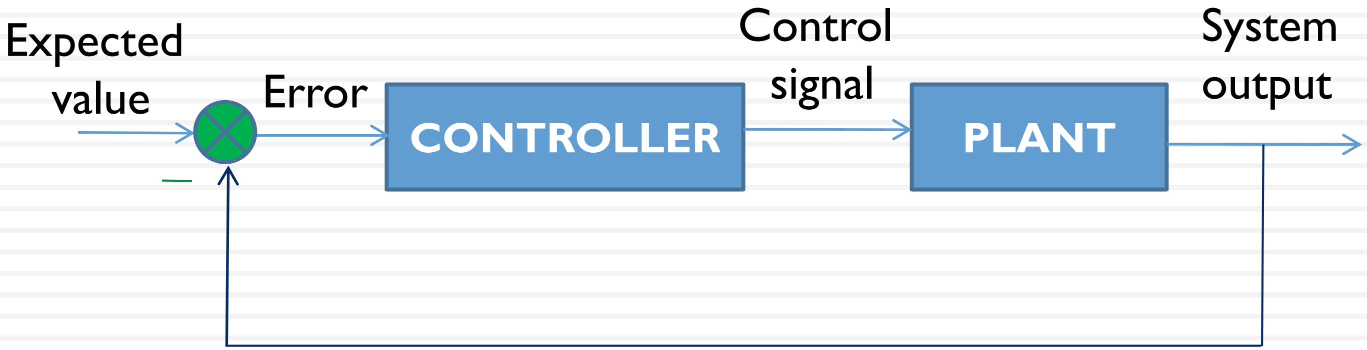
- Some comments on open-loop control systems
  - Simple construction and ease of maintenance.
  - Less expensive than a closed-loop system.
  - No stability problem.
  - Recalibration is necessary from time to time.
  - Sensitive to disturbances, so less accurate.

Open-loop Control Systems (4)

- When should we apply open-loop control?
  - The relationship between the input and output is *exactly known.*
  - There are *neither* internal *nor* external disturbances.
  - Measuring the output precisely is *very hard* or *economically infeasible.*

Closed-loop Control Systems

- Closed-loop control systems are often referred to as feedback control systems.
- The idea of feedback:
  - Compare the *actual output* with the *expected value*.
  - Take actions based on the *difference (error).*



  - This seemingly simple idea is tremendously powerful.
  - Feedback is *a key idea* in the discipline of control.

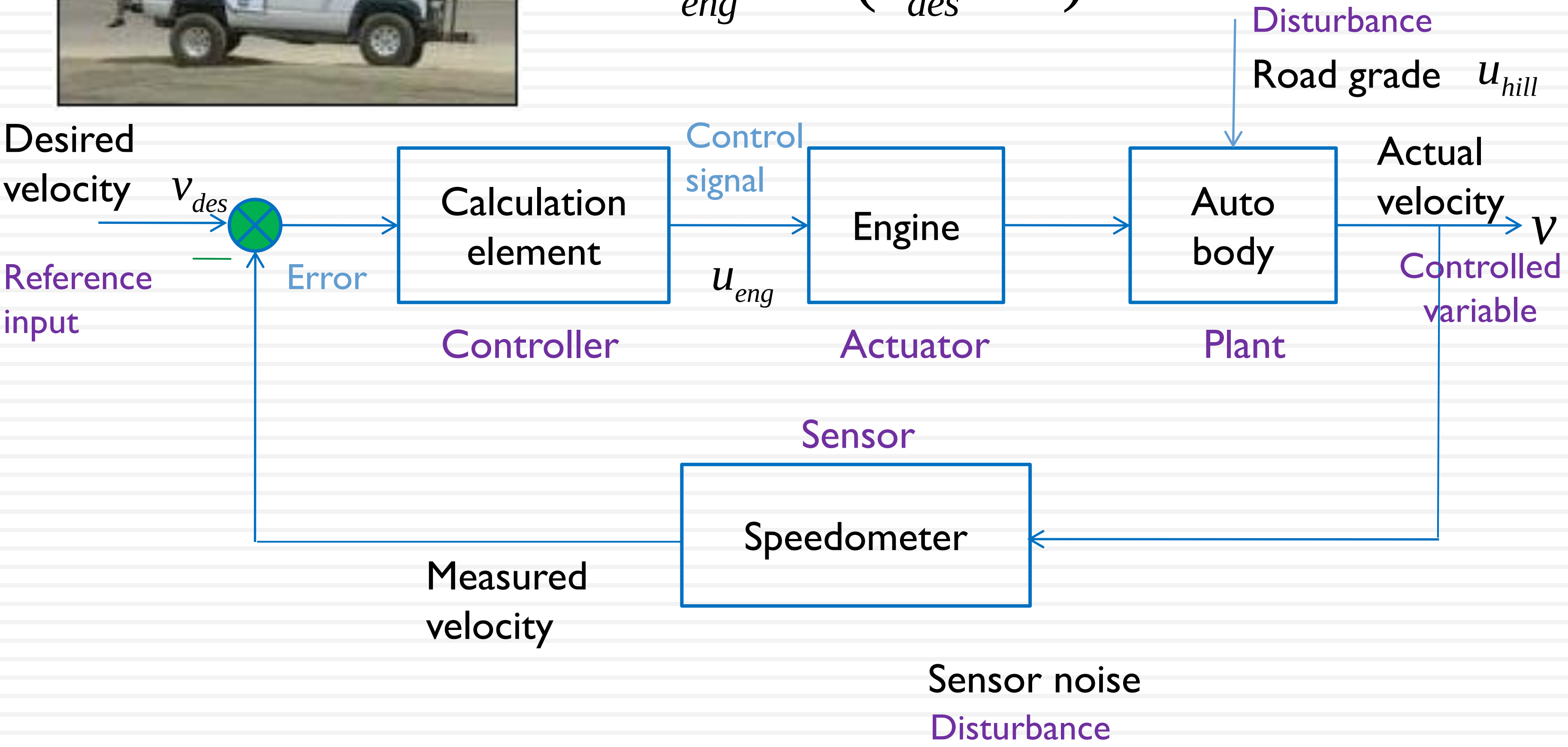
Closed-loop Control Systems (2)

- In practice, feedback control system and closed-loop control system are used interchangeably
- Closed-loop control always implies the use of feedback control action in order to reduce system error

Example: Cruise Control

$$m\dot{v} = -bv + u_{eng} + u_{hill}$$

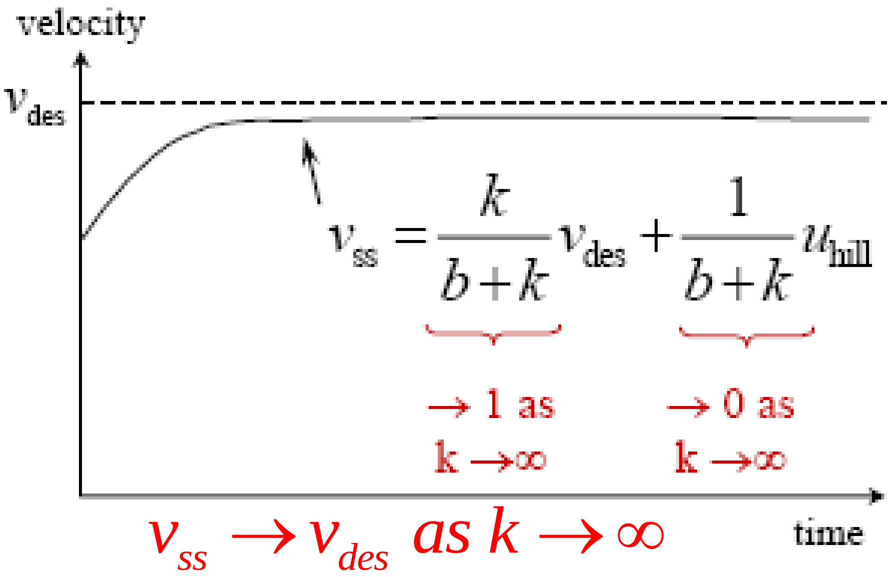
$$u_{eng} = k(v_{des} - v)$$



Example: Cruise Control (2)

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

$$u_{engine} = k(v_{des} - v)$$



$$v_{ss} = \underbrace{\frac{k}{b+k}}_{\substack{\to 1 \text{ as} \\ k \to \infty}} v_{des} + \underbrace{\frac{1}{b+k}}_{\substack{\to 0 \text{ as} \\ k \to \infty}} u_{hill}$$

$$v_{ss} \to v_{des} \text{ as } k \to \infty$$

- **Stability/performance**
  - Steady state velocity approaches desired velocity as $k \to \infty$;
  - Smooth response: no overshoot or oscillations
- **Disturbance rejection**
  - Effect of disturbances (eg, hills) approaches zero as $k \to \infty$
- **Robustness**
  - Results don't depend on the specific values of *b, m or k, for k sufficiently* large

Example: Cruise Control (3)

Note:

- In this example, we ignore the dynamic response of the car and consider only the steady behavior.
  - Dynamics will play a major role in later chapters.

- There are limits on how high the gain k can be made.
  - when dynamics are introduced, the feedback can make the response worse than before, or even cause the system to be unstable.

Feedback control

- Main advantages of feedback:
  - reduce disturbance effects
  - make system insensitive to variations
  - stabilize an unstable system
  - create well-defined relationship between output and reference
- Potential drawbacks of feedback:
  - cause instability if not used properly
  - couple noise from sensors into the dynamics of a system
  - increase the overall complexity of a system

Open-loop vs. Closed-loop

- ☐ Open-loop control

Simple structure, low cost

Easy to regulate

Low accuracy and resistance to disturbance

- ☐ Closed-loop control

Ability to correct error

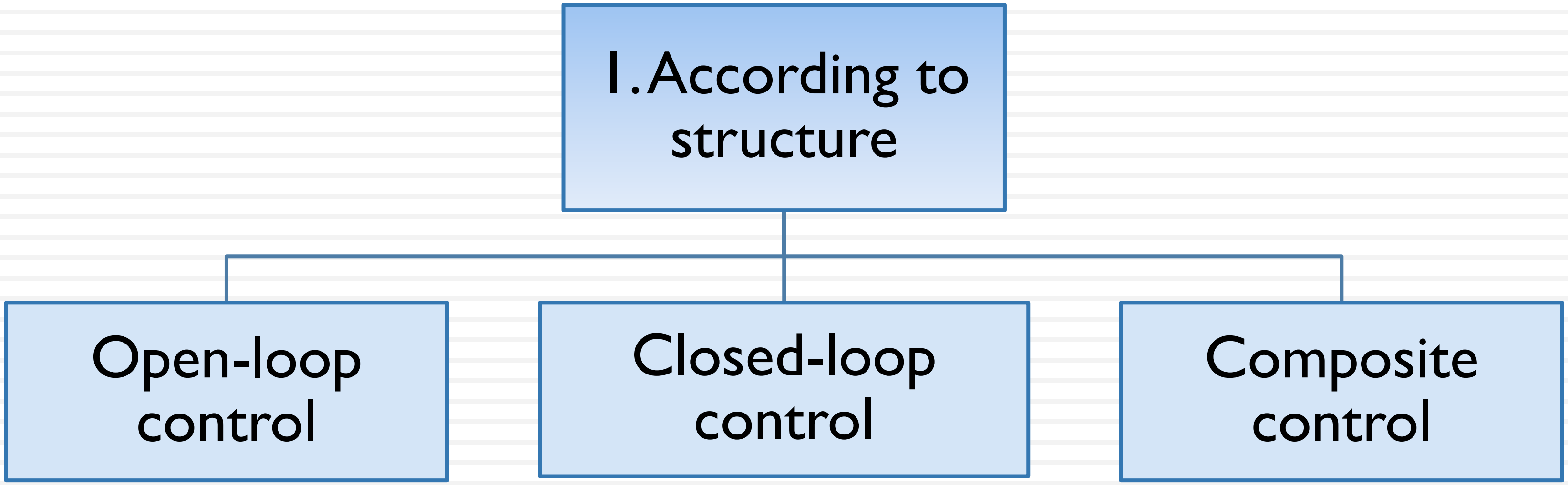
High accuracy and resistance of disturbance

Complex structure, high cost

Selecting parameter is critical (may cause stability problem)

Open-loop＋Closed-loop＝Composite control system

Classification of Control Systems



1. According to structure

- Open-loop control
- Closed-loop control
- Composite control

Classification of Control Systems (2)

2. According to reference input

Constant-value control

- the reference input (expected value) is a constant value
- the controller works to keep the output around the constant value

e.g. constant-temperature control, liquid level control and constant-pressure control.

Servo/tracking control

- the reference input may be unknown or varying
- the controller works to make the output track the varying reference

e.g. automatic navigation systems on boats and planes, satellite-tracking antennas

Programming control

- the input changes according to a program
- the controller works according to predefined command

e.g. numerical control machine

Classification of Control Systems (3)

3. According to system characteristics

$$f(x_1) = y_1 \qquad f(x_2) = y_2$$

⇩ superposition principle

$$f(x_1 + x_2) = f(x_1) + f(x_2) = y_1 + y_2$$

- Linear control system
  - superposition principle applies
  - described by linear differential equations
- Nonlinear control system
  - described by nonlinear differential equations

Classifications of Control Systems (4)

5. According to parameters

- Time-invariant system

  The parameters of a control system are stationary with respect to time

- Time-varying system

  System contain elements that drift or vary with time

  e.g. Guided-missile control system, time-varying mass results in time-varying parameters of the control system

Remarks on Nonlinear Control Systems

- Quite often, nonlinear characteristics are intentionally introduced in a control system to improve its performance or provide more effective control.

  For instance, to achieve minimum-time control, an on-off (bang-bang or relay) type controller is used in many missile or spacecraft control systems

- There are no general methods for solving a wide class of nonlinear systems

Remarks on Digital Control Systems

- A digital control system refers to the use of a digital computer or controller in the system, so that the signals are digitally coded, such as in binary code.
- Digital computers provide many advantages in terms of size and flexibility.
  - The expensive equipment used in a system may be shared simultaneously among several control channels.
  - Digital control systems are usually less sensitive to noise.

Basic Requirements of Control Systems

- Basic requirements for control systems
  - **Stability**: refer to the ability of a system to recover equilibrium
  - **Quickness**: refer to the duration of transient process before the control system to reach its equilibrium
  - **Accuracy**: refer to the value of steady-state error when the transient process ends

(Steady-state error=desired output – actual output)

Basic Requirements of Control Systems (2)

Note:

☐For a control system, the above three performance indices (stability, quickness, accuracy) are sometimes contradictory.

☐ In design of a practical control system, we always need to make a compromise.

Course Outcome

- This course is concerned with the analysis and design of control systems

Analysis	• System modeling, sensitivity and stability
Design	• Time-domain techniques (root-locus analysis); • Frequency-domain techniques (Bode plot, Nyquist stability theory) • State-space methods
Simulation	• Analysis and design using MATLAB