Xi'an Jiaotong-Liverpool University
西交利物浦大学

MEC208 Instrumentation and Control System

2024-25 Semester 2

Dr. Yuqing Chen

Email: Yuqing.chen@xjtlu.edu.cn

Office: EB330

Department of Mechatronics and Robotics

School of Advanced Technology

Module Information

- **Lectures**

Time & Venue:

Group 1: 09:00 – 11:00, Monday, SB123 & 11:00 – 13:00, Thursday, EB138

Group 2: 09:00 – 11:00, Wednesday, SD102 & 11:00 – 13:00, Friday, EB138

Notice:

- Lectures are arranged within Week 1-6, 8-13. Week 7 is non-teaching week.
- Onsite learning is mandatory to every student, please come to lectures and record your attendance
- Video of lectures will still be recorded and will be released to you every week, but will not be broadcasted live

- **Lab**

Electronic Lab

- **Please check your timetable carefully**
- **Time**
    - **14:00-18:00, Monday Week 3 (group 1)**
    - **14:00-18:00, Monday Week 4 (group 2)**
    - **14:00–18:00, Friday Week 3 (group 3)**
- **Venue**
    - **IR112**

- **Lab**

Computing Lab

- **Time – Week 11**
  - **14:00-18:00, Monday (group 1-4)**
  - **Venue: SD546, CBG15E, CBG13, IR112**
- **TA support – Week 11**
  - **14:00-16:00, Wednesday (group 1-4)**
  - **Venue: IR112**
  - **Computer available, come if you have any problems**

Course Information

Initial Assessment:

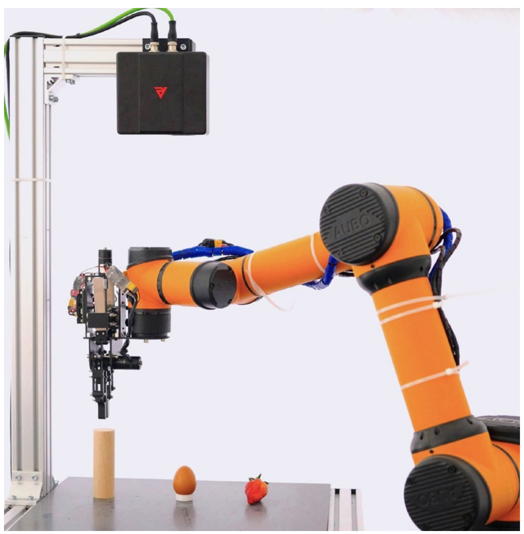
- **Coursework: 2 lab reports (15% each)**
  - Individual work (discussion allowed, plagiarism strictly prohibited)
  - Coursework should be submitted to LM (e-copy)
  - Observe the deadlines, university policy applied for late submissions
- **Final Exam: (70%)**
  - Three-hour closed book exam during examination days (TBD)

Resit Assessment:

- **Resit Exam: (100%)**
  - Three-hour closed book exam after the end of semester 2 (TBD)

My Background

- **Research Interests:**
  - Robotic system design and control
  - Optimal control theory
  - Intelligent control for robotic systems



SURF project in 2022
Paper published in CASE2023

SURF project in 2023
Received Group winner award

Contact Information

- **Instructor: Dr. Yuqing Chen**
  - Email: Yuqing.Chen@xjtlu.edu.cn
  - Office: EB330
  - Office hour: 2-4pm, Tuesday
  - Office telephone number: +86 (0512) 8188 8785
- **Instructor: Dr. Chee Shen Lim**
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  - Office: SC469
  - Office hour: 2-4pm, Thursday
  - Office telephone number: +86 (0512) 8816 7127

Module Goal

Study on control system design with sensor and transducer is required to get an ability to analyse the measurement, controller design, and system performance analysis.

Module covers from the understanding of sensor/transducer itself and its circuit design to the integration of controller design with data acquisition unit.

Learning Outcomes

A. Understand instrumentation process with sensor configuration and evaluate physical effect from measurement.

B. Understand instrumentation system process (sensor, transducer, actuator) and its signal flow (continuous, digital), and analyse first- and second-order system response, and transfer function from Laplace transform.

C. Decide system stability with Routh Array, Root Locus and Nyquist plot.

D. Design feedback controller to stabilize overall system (PID controller, State feedback controller).

E. Combine control system with sensor and transducer.

Reading Materials

Mandatory Textbooks

Title	Author	ISBN/Publisher
MODERN CONTROL SYSTEMS (14TH EDITION)	RICHARD C DORF, ROBERT H. BISHOP	9780137307098 /PEARSON

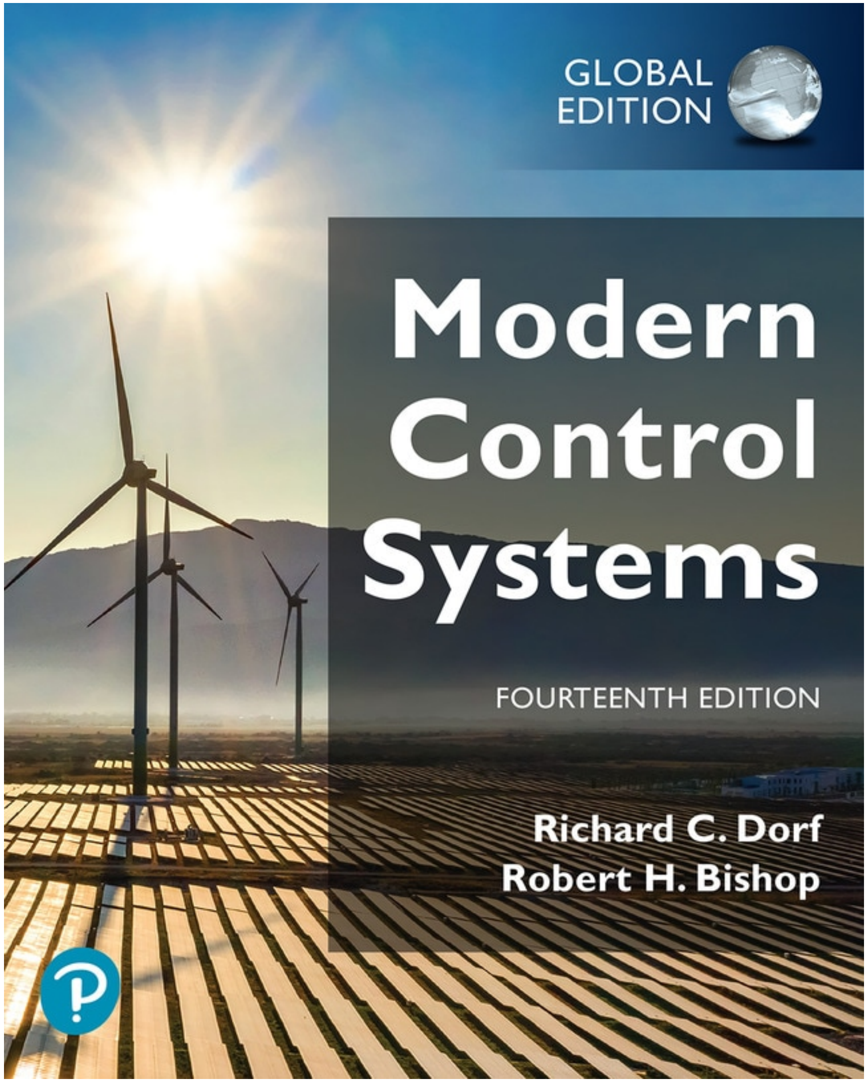
Optional Textbooks

Title	Author	ISBN/Publisher
MECHATRONICS : ELECTRONIC CONTROL SYSTEMS IN MECHANICAL AND ELECTRICAL ENGINEERING (7TH EDITION)	WILLIAM BOLTON	9781292250977 /PEARSON
INSTRUMENTATION AND CONTROL SYSTEMS (3RD EDITION)	WILLIAM BOLTON	9780128234716 /NEWNES

Reference Textbooks

Title	Author	ISBN/Publisher
CONTROL SYSTEMS ENGINEERING (8TH EDITION)	NORMAN S. NISE	9781119592921 /WILEY

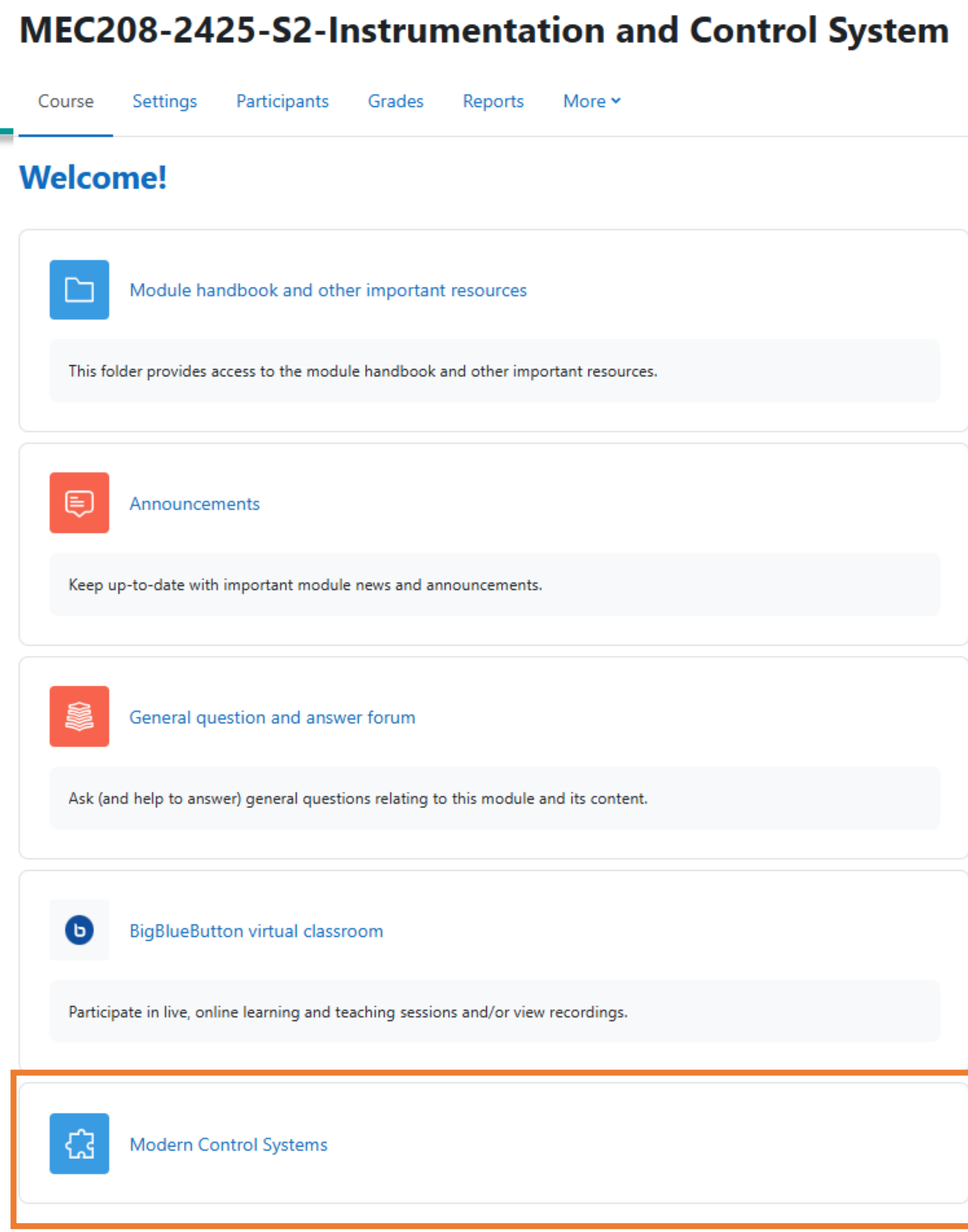
Mandatory Book



- Textbook is provided in electronic version
- Two ways to access the textbook:
  1. LMO
  2. Website

Mandatory Book

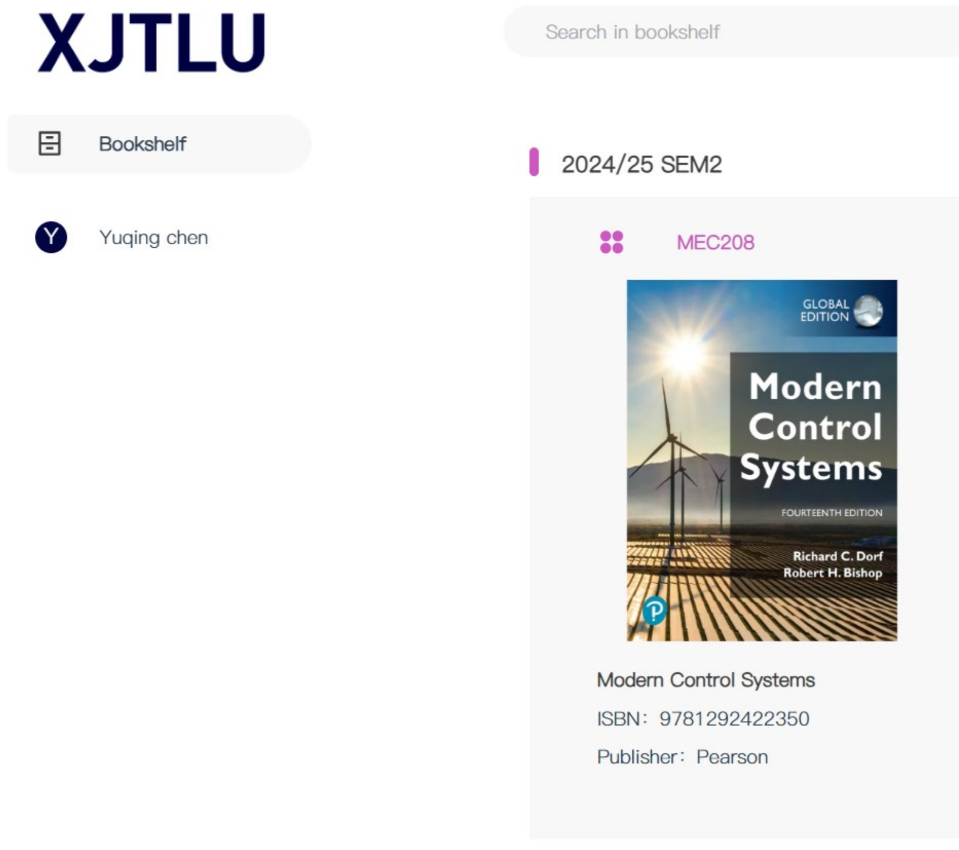
- Access via LMO



Mandatory Book

- Access via link:

https://etextbook.xjtlu.edu.cn/



Lecture 1

Outline

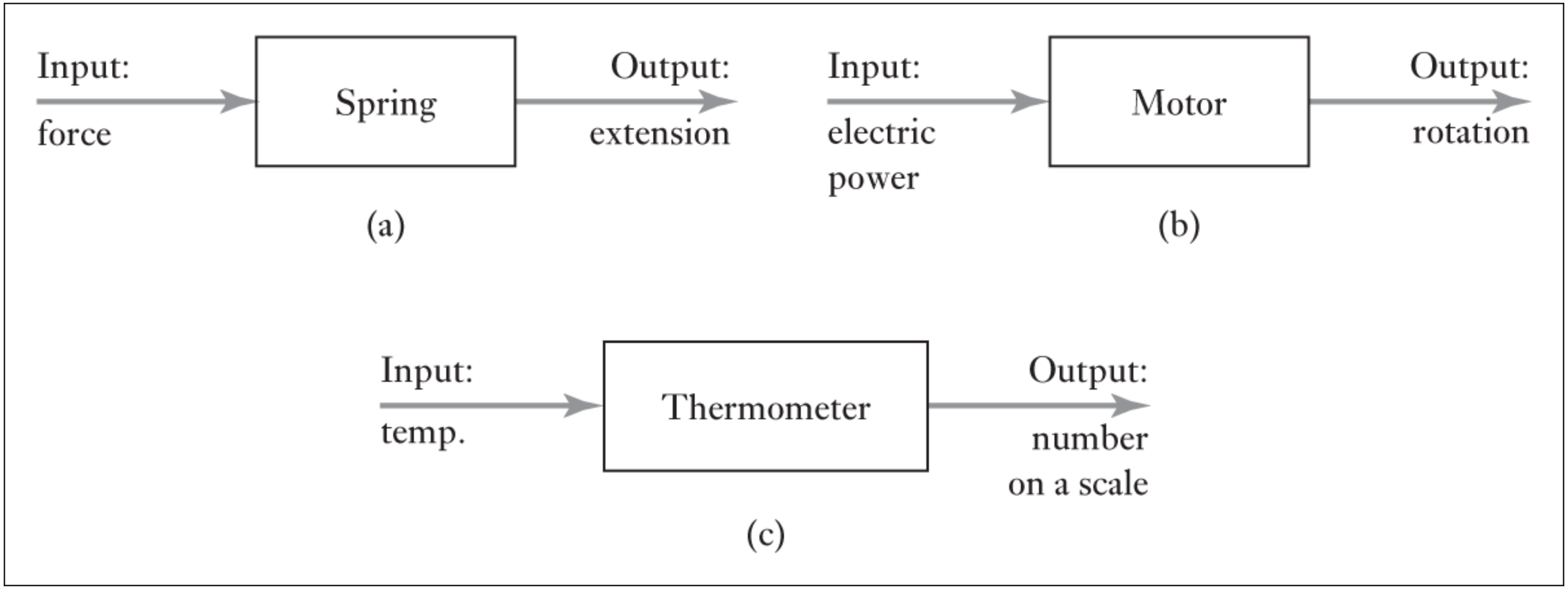
- Definition of Systems
- Instrumentation System: Definitions and Basic Concepts
- Overview of Control Systems
- Static Characteristics of Sensor Performance
- Dynamic Characteristics of Sensor Performance

Outline

- **Definition of Systems**
- Instrumentation System: Definitions and Basic Concepts
- Overview of Control Systems
- Static Characteristics of Sensor Performance
- Dynamic Characteristics of Sensor Performance

System

A **System** can be thought of as a box or block diagram which has an input and output where we are concerned not with what goes on inside the box but with only the relationship between the output and the input.



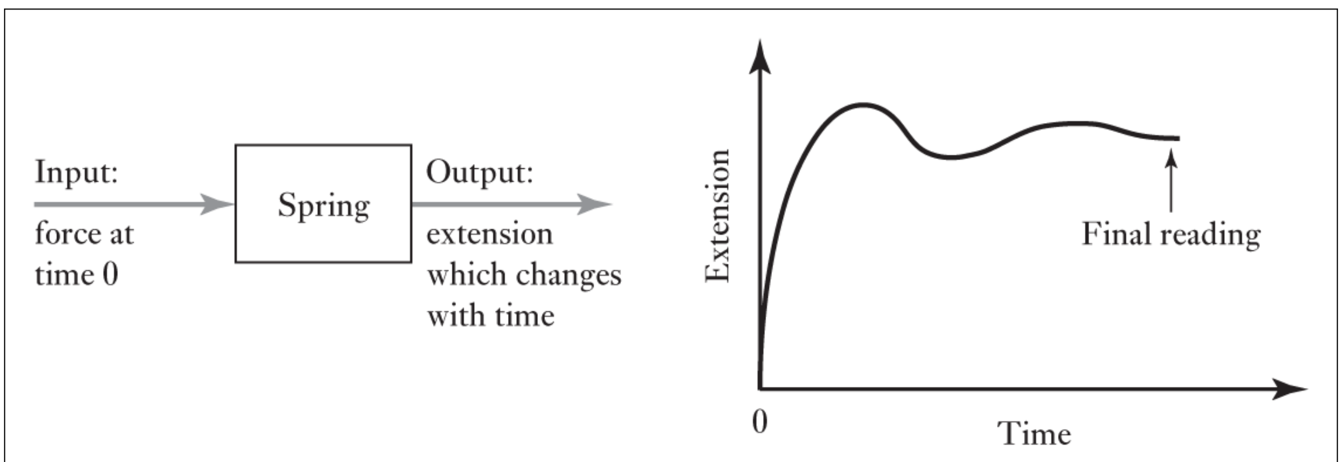
Examples of systems: (a) spring, (b) motor, (c) thermometer.

Modelling Systems

The response of any system to an input is not instantaneous. The response of systems are functions of time.

In order to know how systems behave when there are inputs to them, we need to devise models for systems which relate the output to the input, so that we can work out, for a given point, how the output will vary with time and what it will settle down to.

For example, for the spring system, $F = kx$ only describes the force (F)–extension (x) relationship when steady-state conditions occur. When the force is applied, oscillations will occur before the spring settles down to its steady-state extension value.



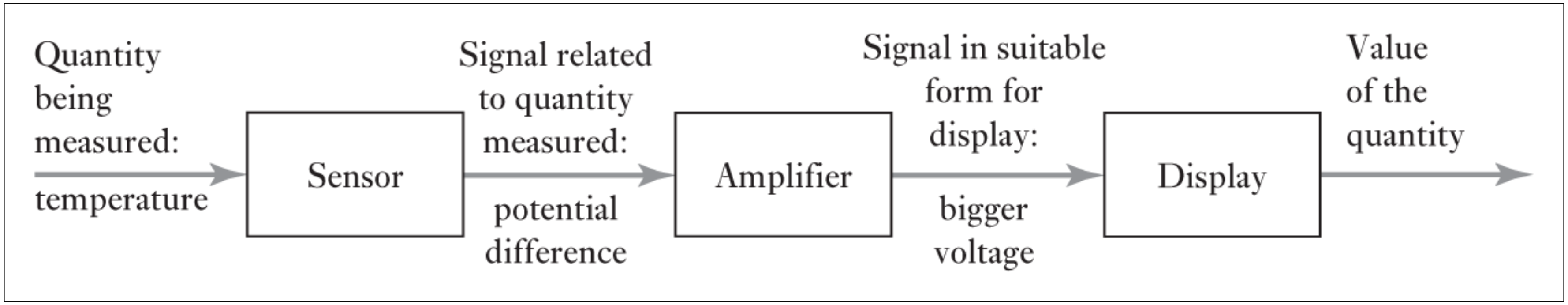
Outline

- ☐ Definition of Systems
- ☐ **Instrumentation System: Definitions and Basic Concepts**
- ☐ Overview of Control Systems
- ☐ Static Characteristics of Sensor Performance
- ☐ Dynamic Characteristics of Sensor Performance

Instrumentation / Measurement System

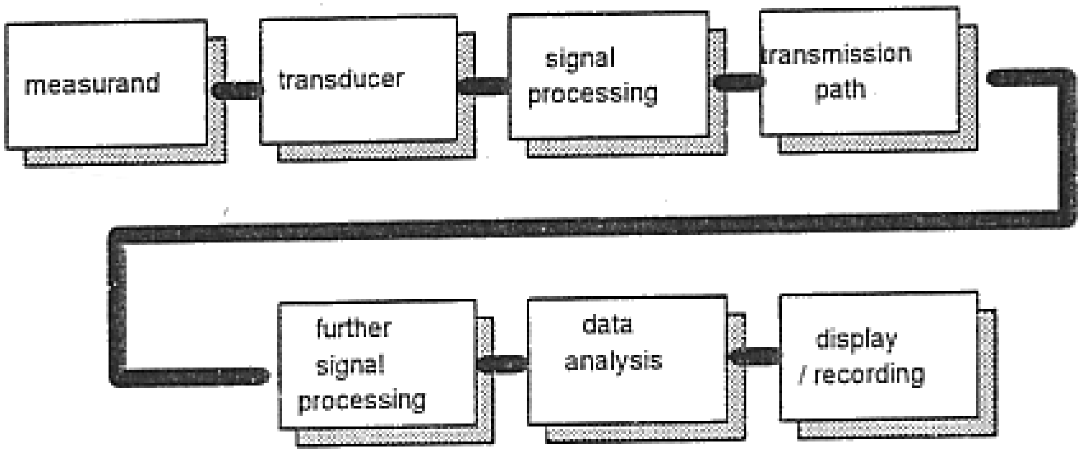
An **instrumentation / measurement system** can be thought of as a box which is used for making measurements. Generally, it is considered to be made of three basic elements:

1. A sensor responds to the quantity being measured by giving as its output a signal which is related to the quantity;
2. A signal conditioner takes the signal from the sensor and manipulates it into a condition which is suitable either for display, record, transmission or use of control;
3. A display system displays the output from the signal conditioner.



Other concepts

An Instrumentation System



- Measurand

  - the physical quantity being measured, e.g. temperature, strain, displacement, air flow etc.

- Transmission Path

  - the medium used to transmit data, e.g. optical fiber, radio, electrical cables, pneumatic pipes etc.

Outline

- Definition of Systems
- Instrumentation System: Definitions and Basic Concepts
- **Overview of Control Systems**
- Static Characteristics of Sensor Performance
- Dynamic Characteristics of Sensor Performance

Control Systems

A Control system is an interconnection of components forming a system configuration that will provide a **desired** system response.

- The component to be controlled is called **process**.
- The input-output relationship represents the cause-and-effect relationship of the process, which in turn represents a processing of the input signal to provide a desired output signal.
  - control a motor to rotate faster, 30r/min → 60r/min
  - control a robot to move, 3m → 6m

Control Systems

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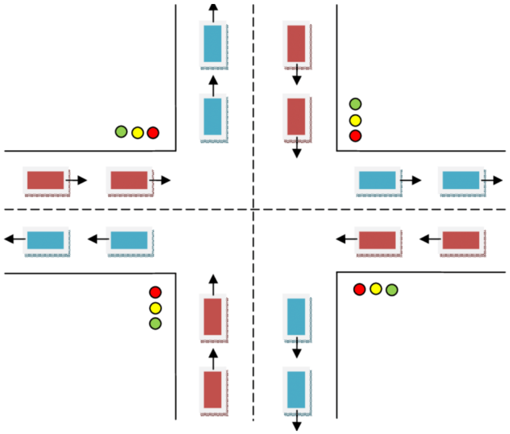
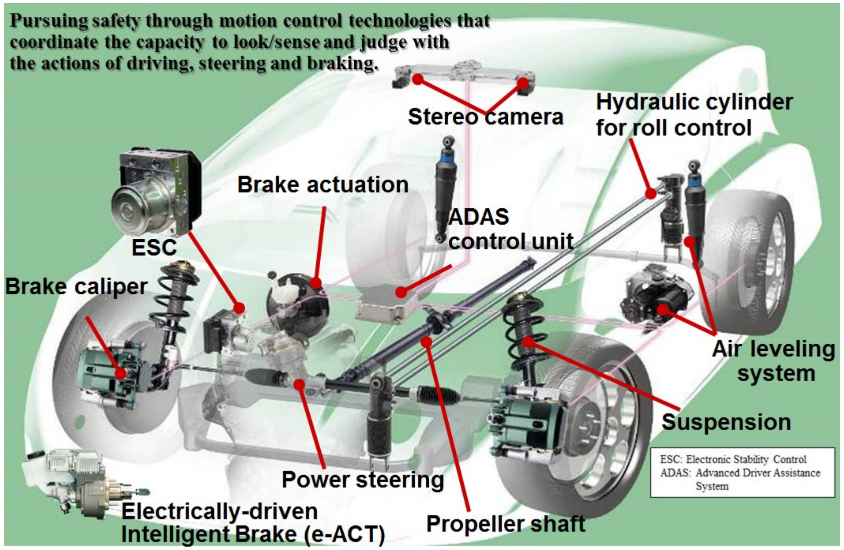
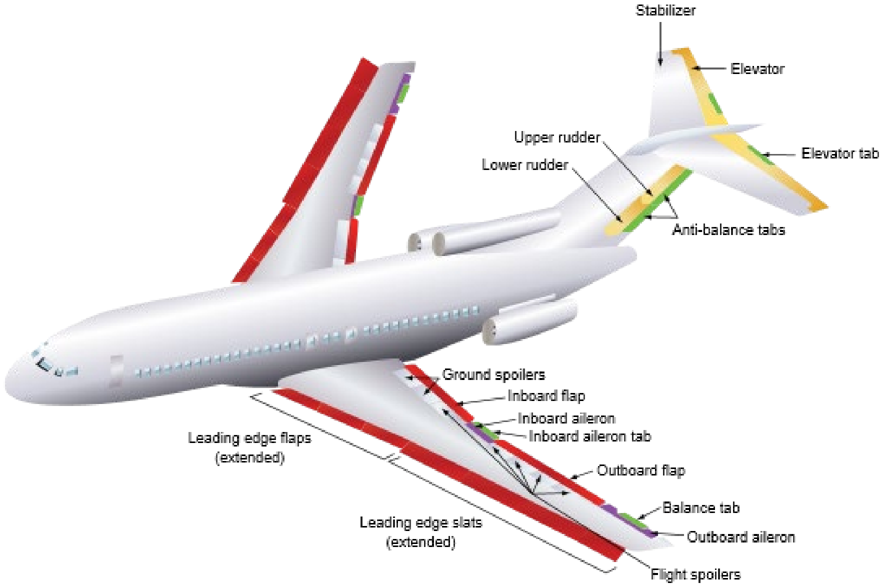
- The component to be controlled is called **process**.
- The input-output relationship represents the cause-and-effect relationship of the process, which in turn represents a processing of the input signal to provide a desired output signal.
- The basis for analyzing a system is linear system theory. Control system is designed based on mathematical background, there are various methodology to solve a given problem.

Where Control Systems are Used?

- Transportation
  - Aeroplanes
  - Cars
  - Traffic control





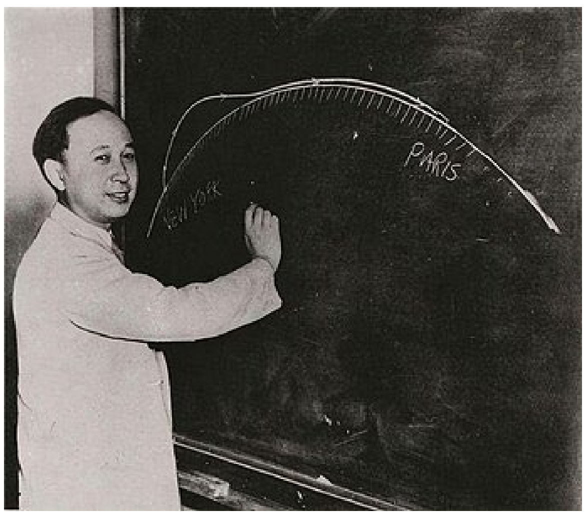


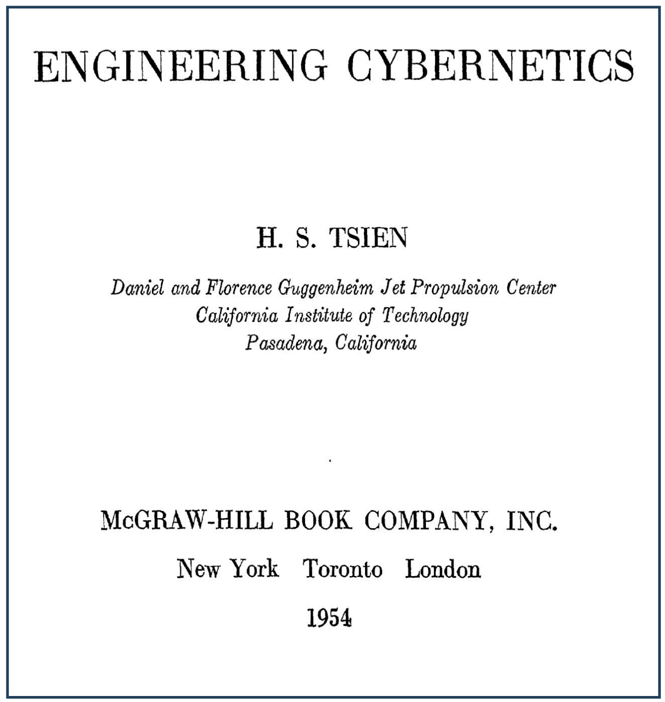
Where Control Systems are Used?

- Industrial process
  - Energy
  - Chemistry

Where Control Systems are Used?

- Military area
  - Rocket
  - Tank





ENGINEERING CYBERNETICS

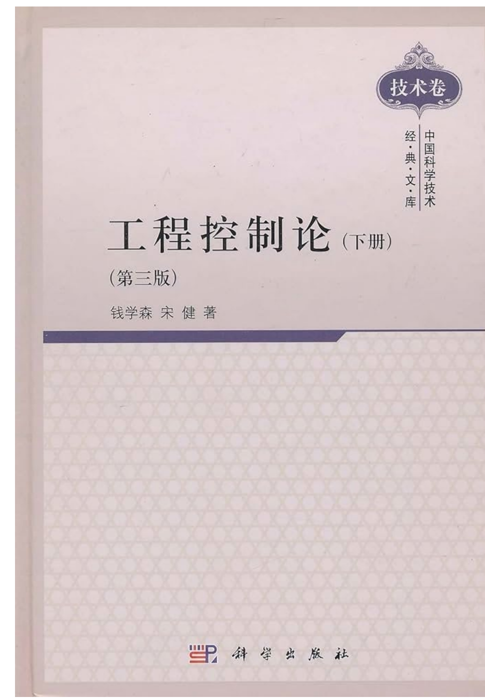
H. S. TSIEN

Daniel and Florence Guggenheim Jet Propulsion Center
California Institute of Technology
Pasadena, California

McGRAW-HILL BOOK COMPANY, INC.

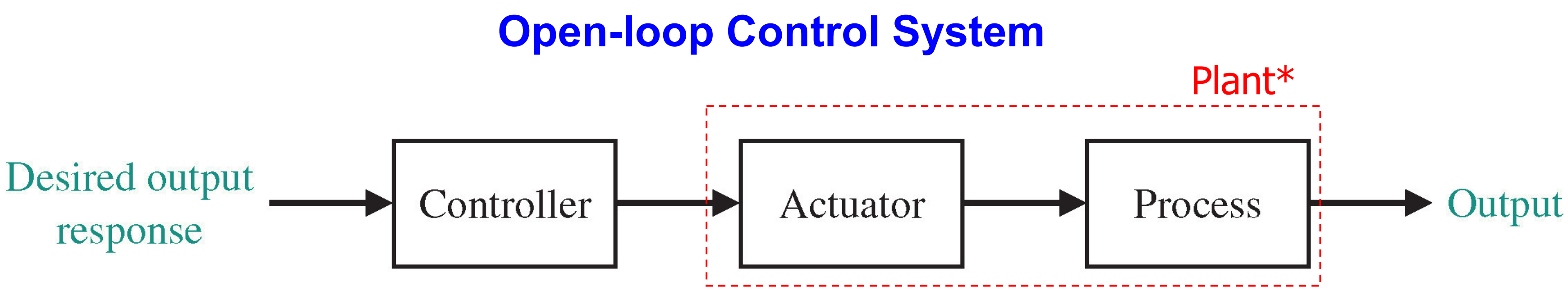
New York Toronto London

1954



Open-loop Control System

- An open-loop control system utilizes an actuating device (actuator) to control the process directly without using feedback to obtain the desired response.
- An open-loop control system is a control system **without** feedback.

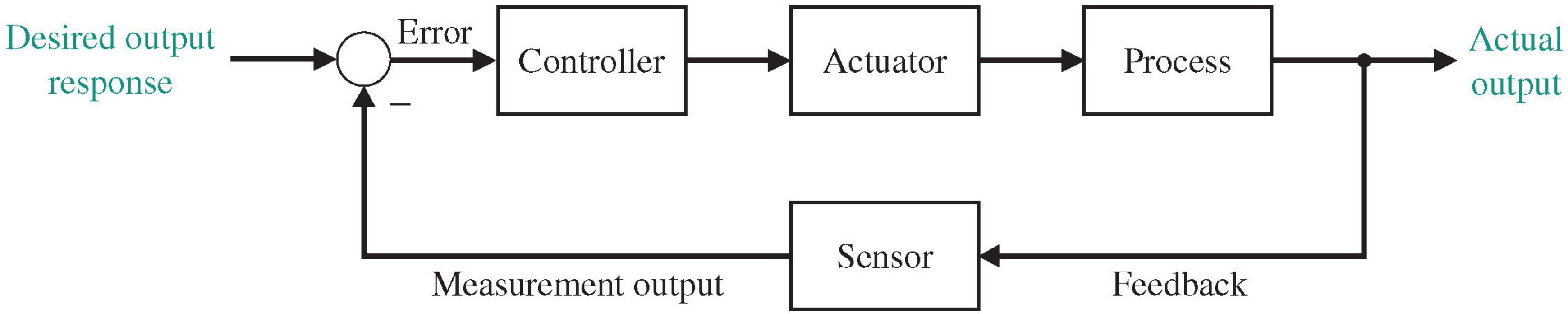


**The plant is the to-be-controlled system.*

Closed-loop Control System

- In contrast to open-loop control system, a closed-loop control system uses a measurement of the output and feedback of this signal for compare it with the desired output (reference or command).
- The measure of the output is called the feedback signal.
- When the output is subtracted from input and the difference is used as the input signal to the controller, it is called a negative feedback control system.

Closed-loop Control System



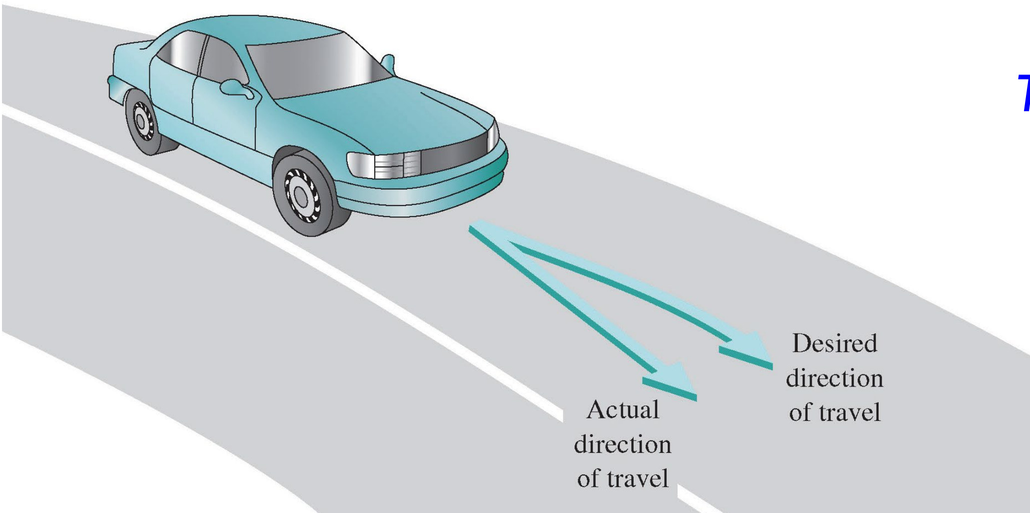
Example 2.1: Toaster

❓: **Is it OPEN-loop or CLOSED-loop system ?**

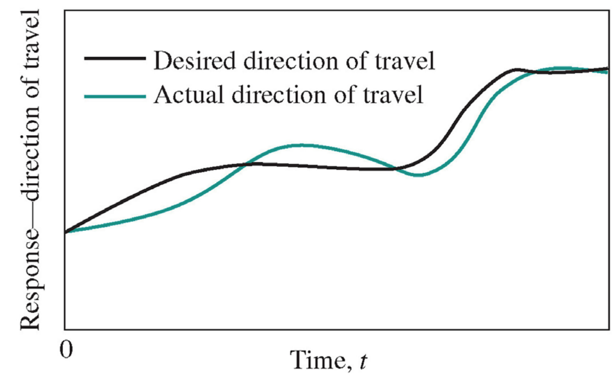
To adjust the desired toast colour, the user adjusts the input time or the preset temperature for toasting.

- **Input**: toast desired color → user adjusts input time.
- **Output**: toasted bread
- What will happen if the components (consequently the system characteristics) changes with time ?

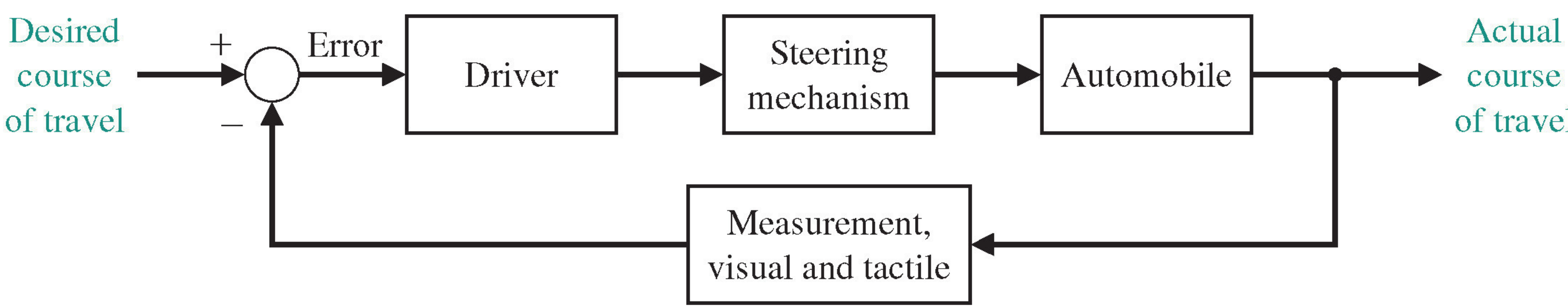
Example 2.2 Automated Vehicles



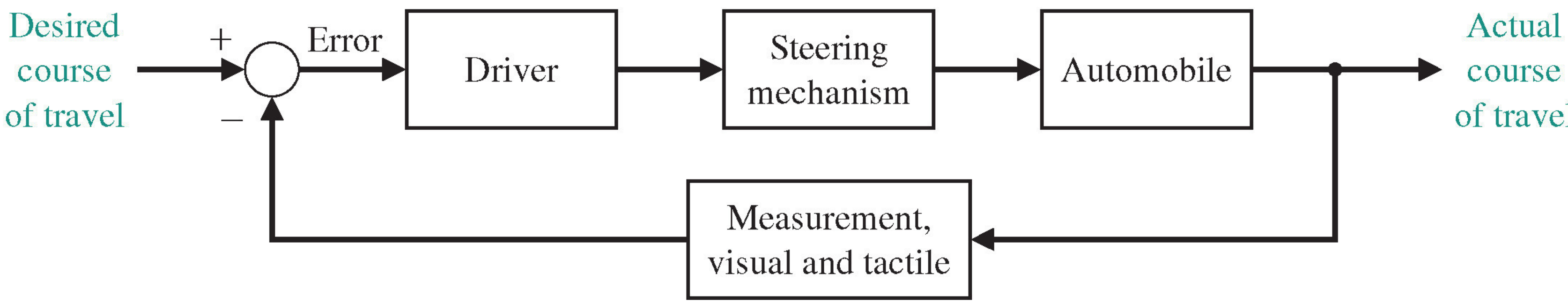
Typical direction-of-travel response.



Automobile steering control system



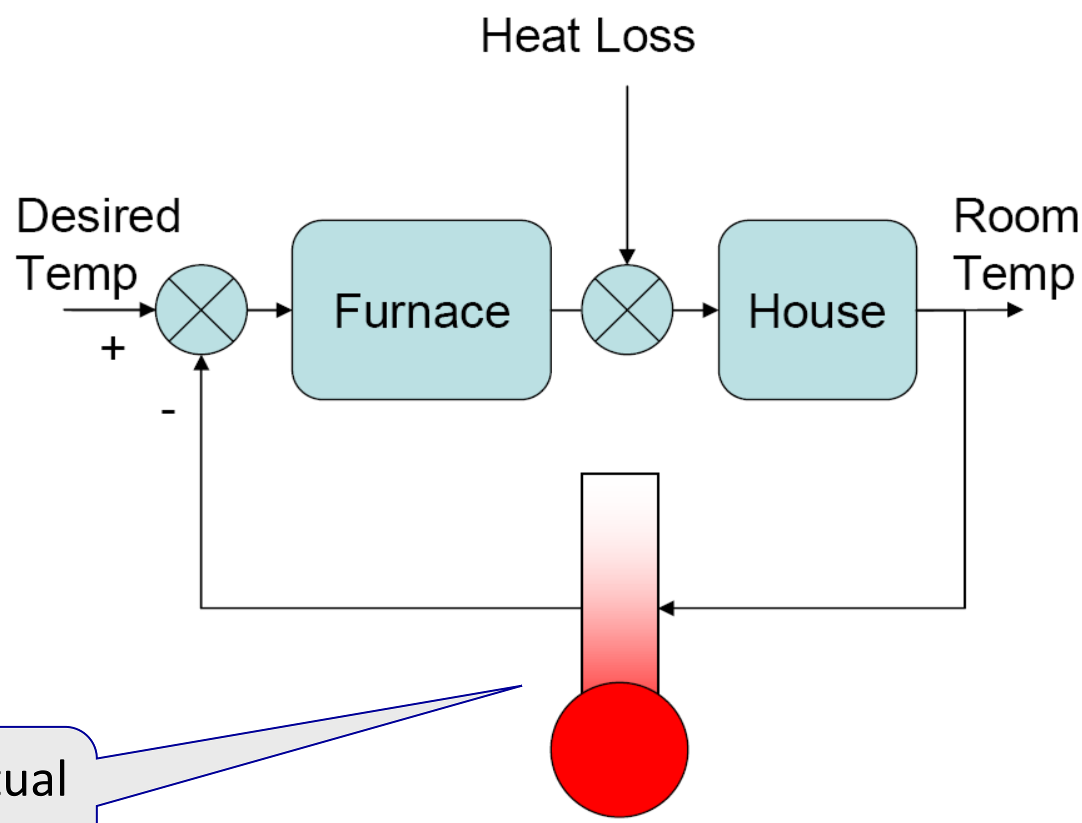
Automobile steering control system



- **Input:** desired course of travel
- **Output:** actual course of travel
- **Sensor:** visual and tactile
- **Actuator**: steering wheel mechanism

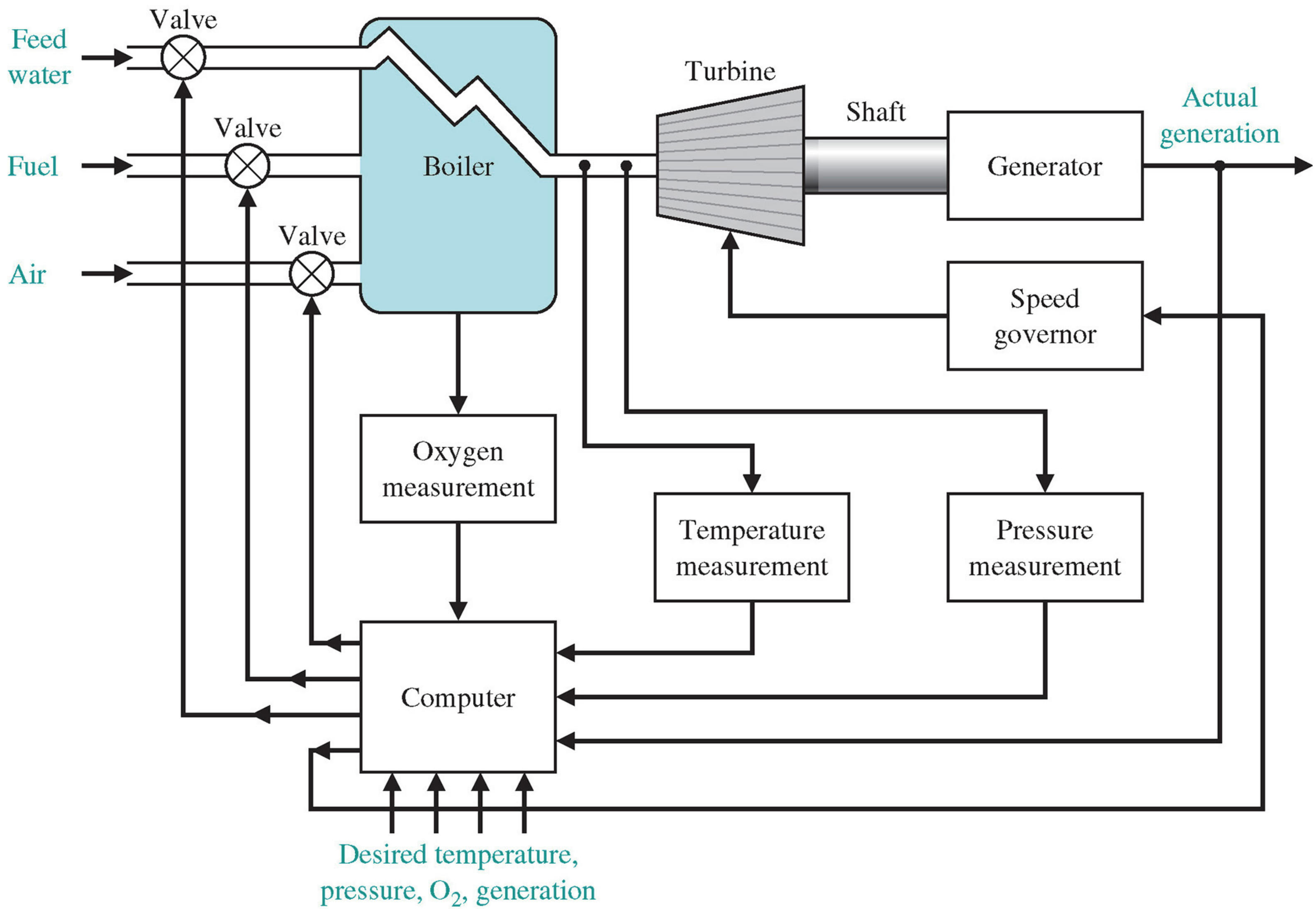
Example 2.3: Room Temperature Controller

Room Temperature Controller



Measure the actual temperature

Example 2.4: Coordinated Control System For A Boiler-generator

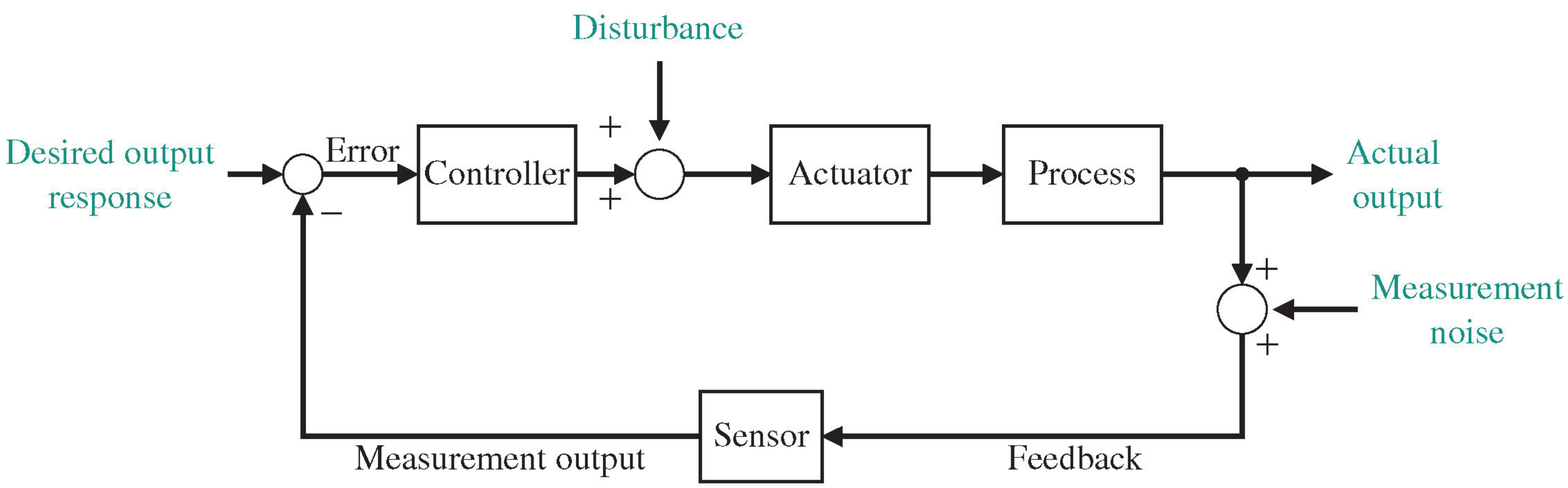


Example 2.4 (cont'd)

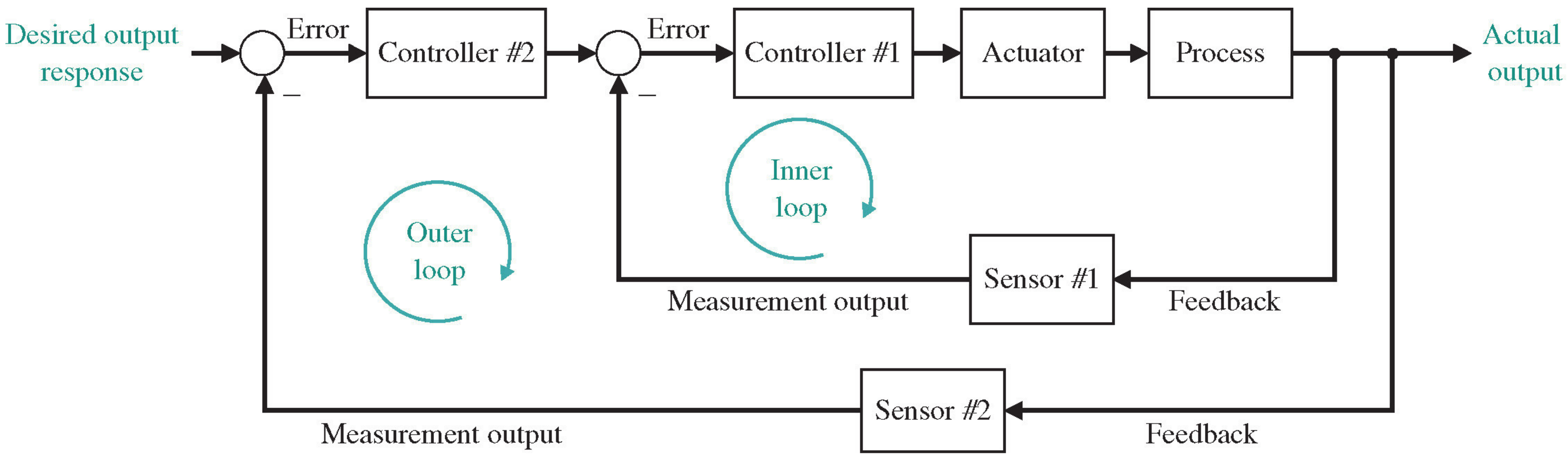
- The modern, large-capacity plants, which exceed several hundred megawatts, require automatic control systems that account for the interrelationship of the process variables and optimum power production;
- It is common to have 90 or more manipulated variables under coordinated control. A simplified model showing several of the important control variables of a large boiler-generator system. This is an example of the importance of measuring many variables, such as pressure and oxygen, to provide information to the computer for control calculations.

Advantages of Closed-loop Control System

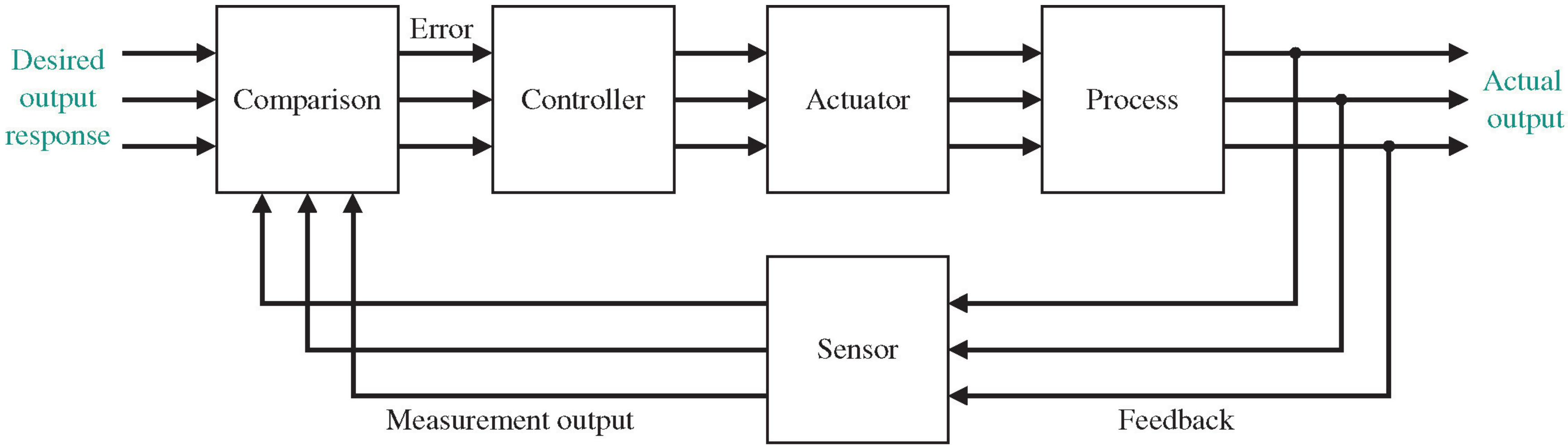
As we will discuss in later lectures, closed-loop control system has many advantages over open-loop control systems, including the ability to reject external disturbance and attenuate measurement noise, which are inevitable in real-world applications and must be addressed in practical control system designs.



Multiloop Feedback Control System

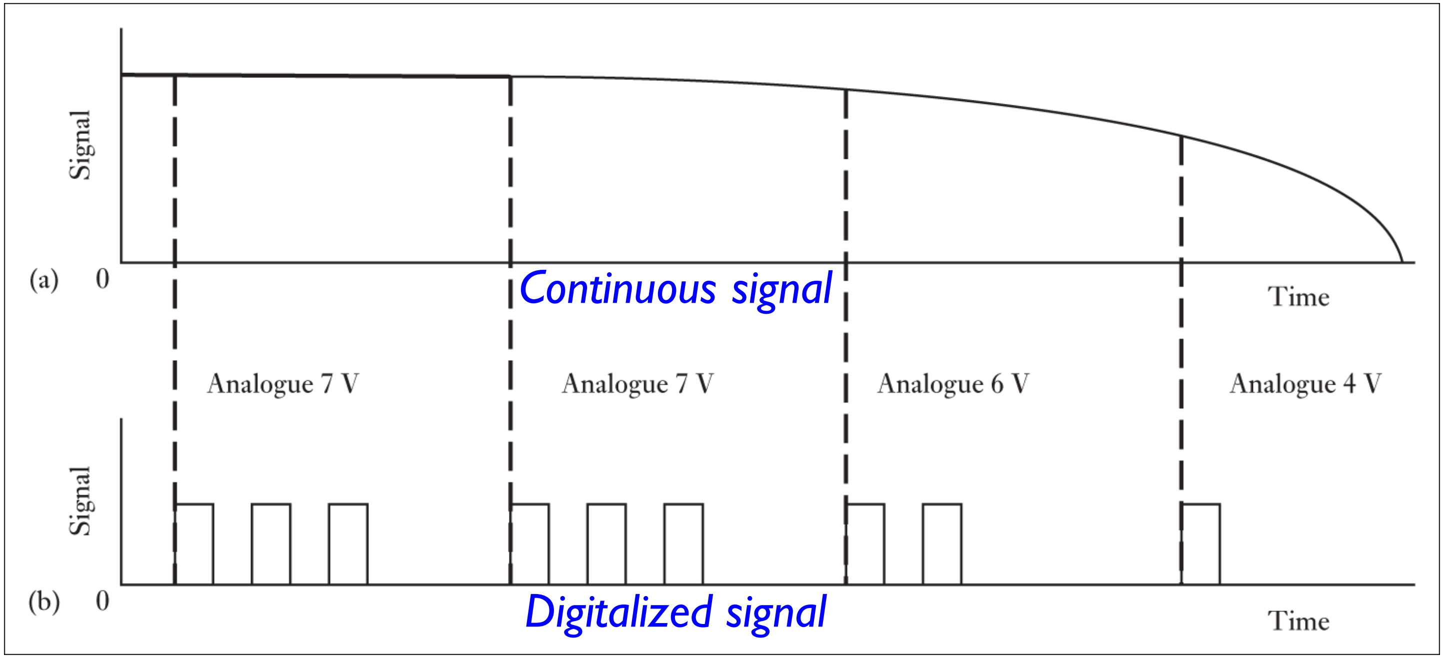


Multivariable Control System

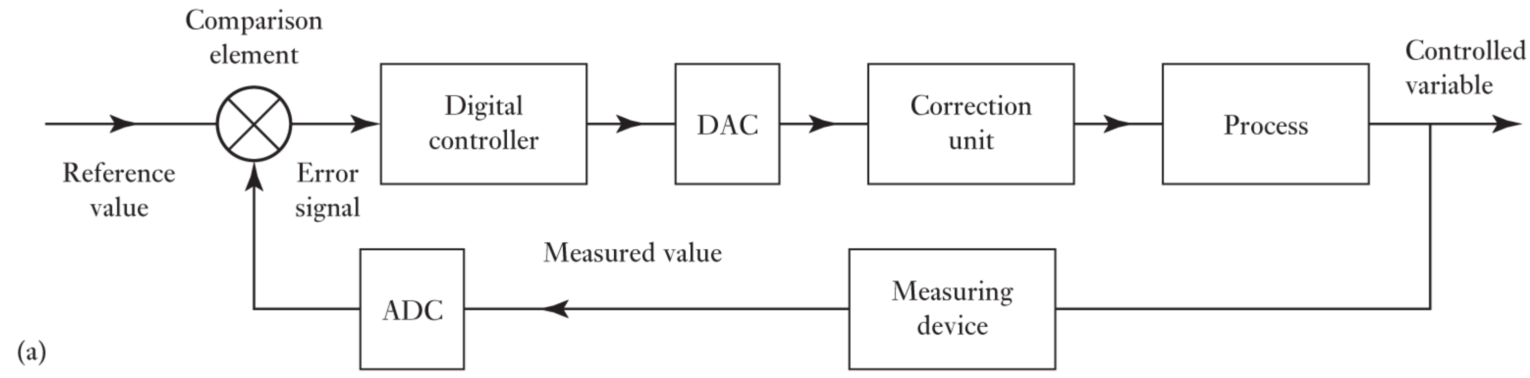


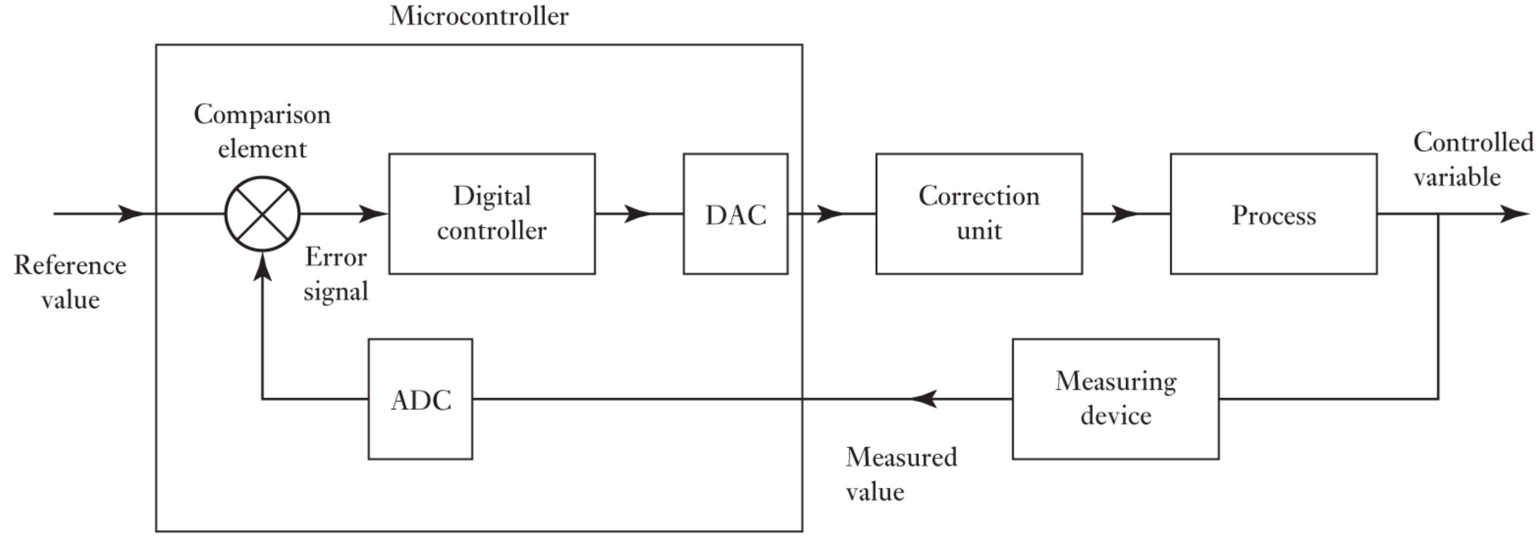
Analogue and Digital Control System

- **Analogue systems** are systems where all the signals are continuous functions of time;
- **Digital systems** are ones where all the signals can be considered to be a sequence of on/off signals.



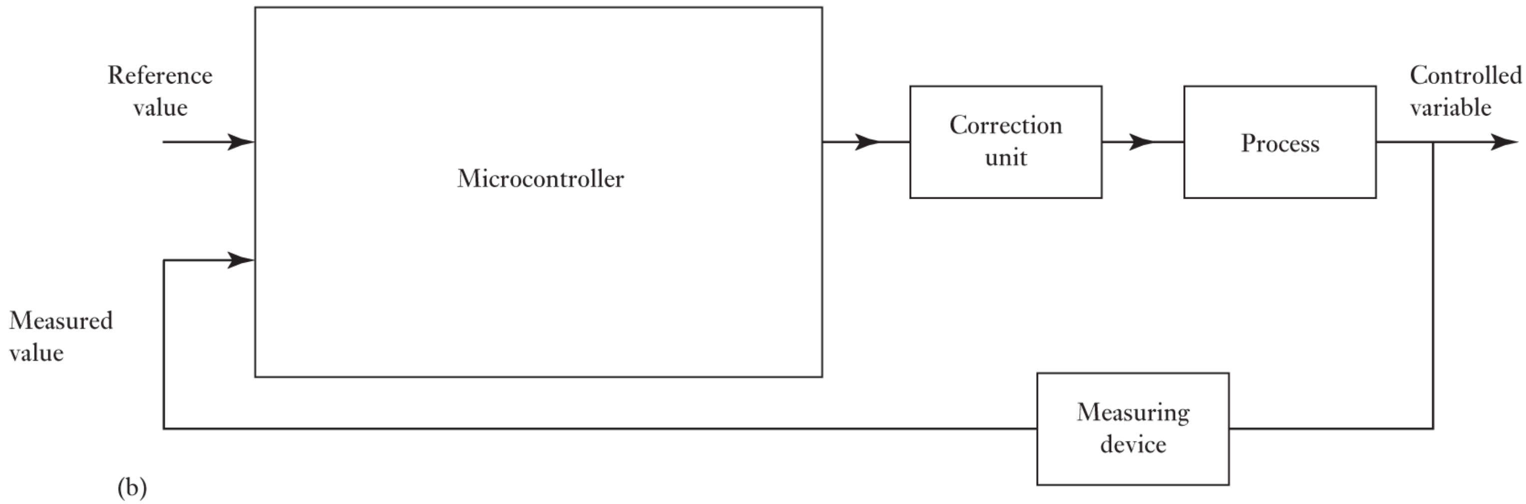
Basic Elements of a Digital Closed-loop Control System





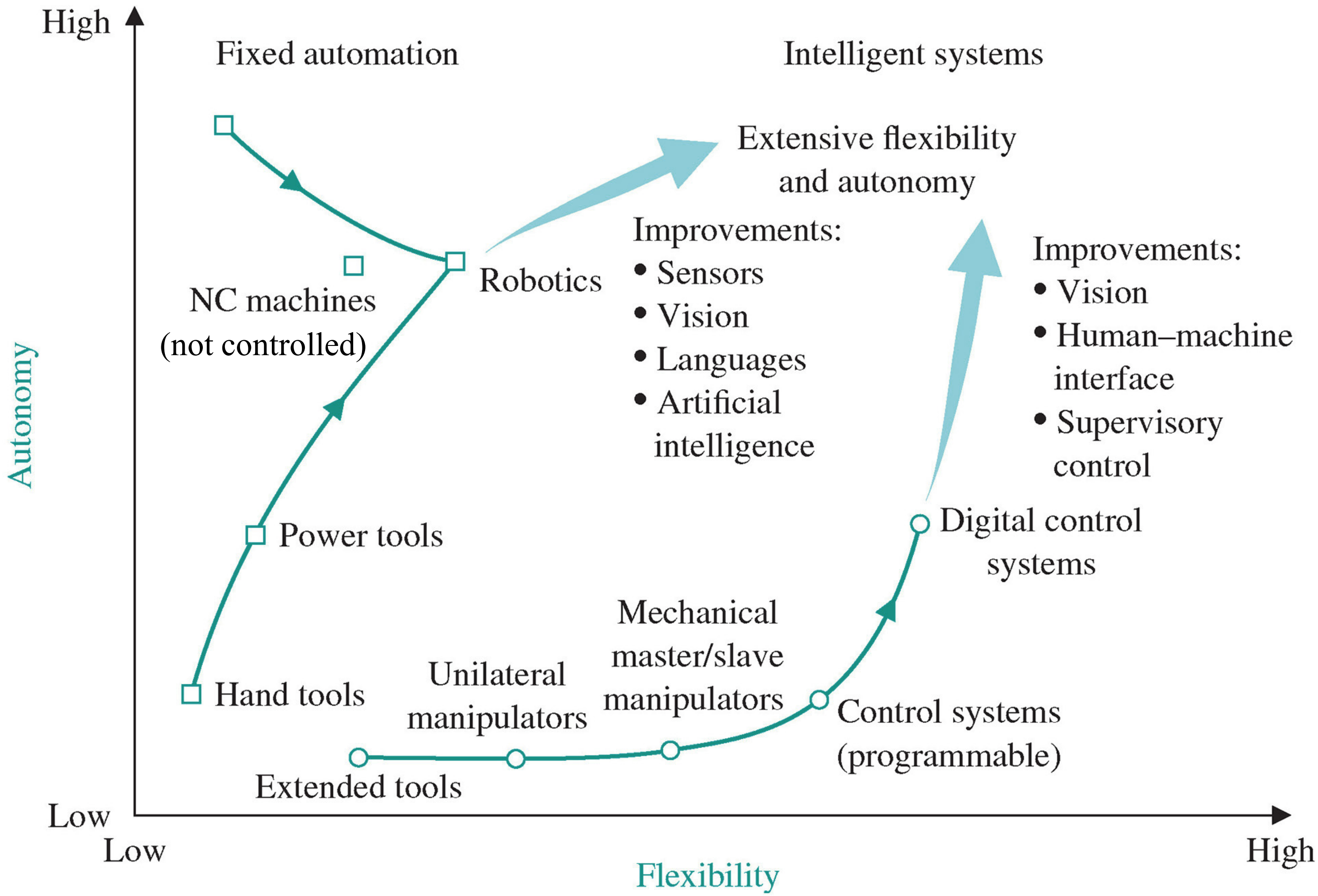
ADC: analogue-to-digital converter; DAC: digital-to-analogue converter.

Features of Digital Control Systems



- Most of the situations being controlled are analogue in nature, it involves ADCs and DACs for digital control systems, it might seem to be adding a degree of complexity;
- However, there are some very important advantages: digital operations can be controlled by a program, i.e., a set of stored instructions; information storage is easier, accuracy can be greater, digital circuits are less affected by noise and also are generally easier to design.

Future Evolution of Control System and Robotics



Outline

- Definition of Systems
- Instrumentation System: Definitions and Basic Concepts
- Overview of Control Systems
- **Static Characteristics of Sensor Performance**
- Dynamic Characteristics of Sensor Performance

Sensors vs Transducers

- The term sensor is used for an element which produces a signal related to the quantity being measured, i.e., electrical resistance temperature element.
- The term transducer is often used in place of the term sensor. Transducers are defined as elements that when subject to some physical change experience a related change.

Thus sensors are transducers.

Sensors vs Transducers

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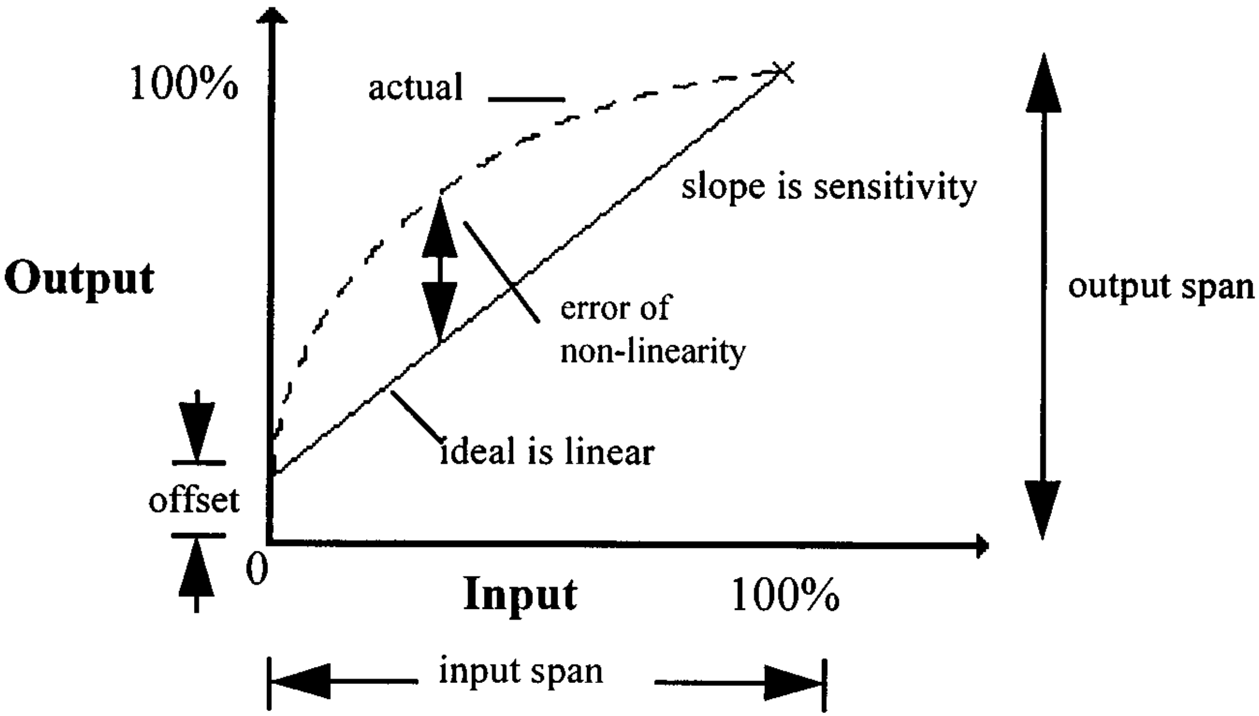
Thus sensors are transducers.

A measurement system may use transducers, in addition to the sensors, in other parts of the system, to covert signals in one form to another form.

Static Characteristics of Sensor Performance



- Range / span
- Error
- Accuracy
- Precision
- Sensitivity
- Resolution
- Hysteresis error
- Non-linearity error
- Repeatability/ reproducibility
- Dead band / time
- Etc.

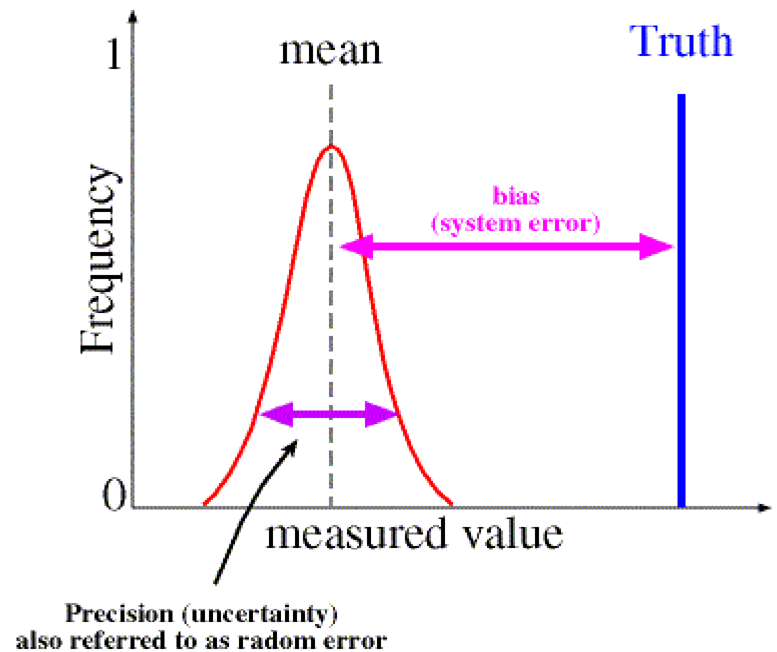
Factors Affecting Accuracy

- Transducer placement: the transducer must be located at an appropriate position and with an appropriate orientation to measure the measurand accurately;
- The introduction of a transducer may affect the measurand;
- The interconnection of the system may cause electrical loading effects;
- Other physical parameters may interact with the system and affect the measurement;
- The transducers themselves introduce a source of error.

Measurement Error: Systematic Error

- **Systematic Error (bias)** sources:
  - usually those that change the input–output response of a sensor resulting in mis-calibration
  - aging, damage or abuse of the sensor
  - measurement process itself changes the intended measurand
  - the transmission path
  - human observers

✓ Systematic error can be corrected by some methods if the error source is known.

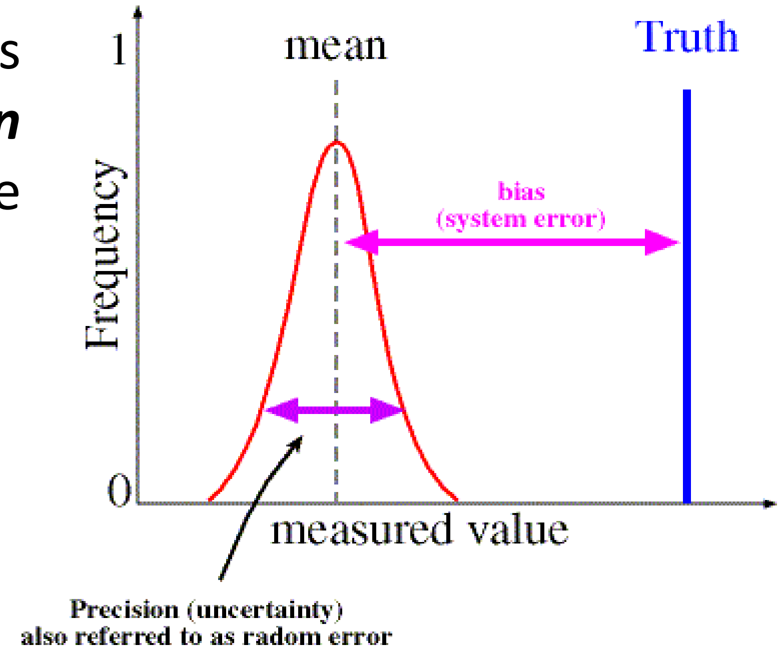


Measurement Error: Random Error

- **Random Error (noise)** sources:
  - usually unknown and unpredictable changes in the measurement
  - may occur in the measuring instruments or in the environmental conditions

Random error is often referred to as noise, and exhibit a ***Gaussian distribution*** when repeating a large number of measurements.

◆ Random error can NOT be completely eliminated.



Measurement Uncertainty

Accuracy:

- defined as the difference between the true value of the measurand and the measured value indicated by the instrument;
- determined by systematic error;
- usually expressed as a percentage of the full-scale deflection (FSD) of the transducer or system.

For example:

A system might have an accuracy of $\pm 1\%$ of FSD. If the FSD=10A, then the accuracy is

$$10 \times \pm 1\% = \pm 0.1\mathrm{A}$$

Measurement Uncertainty

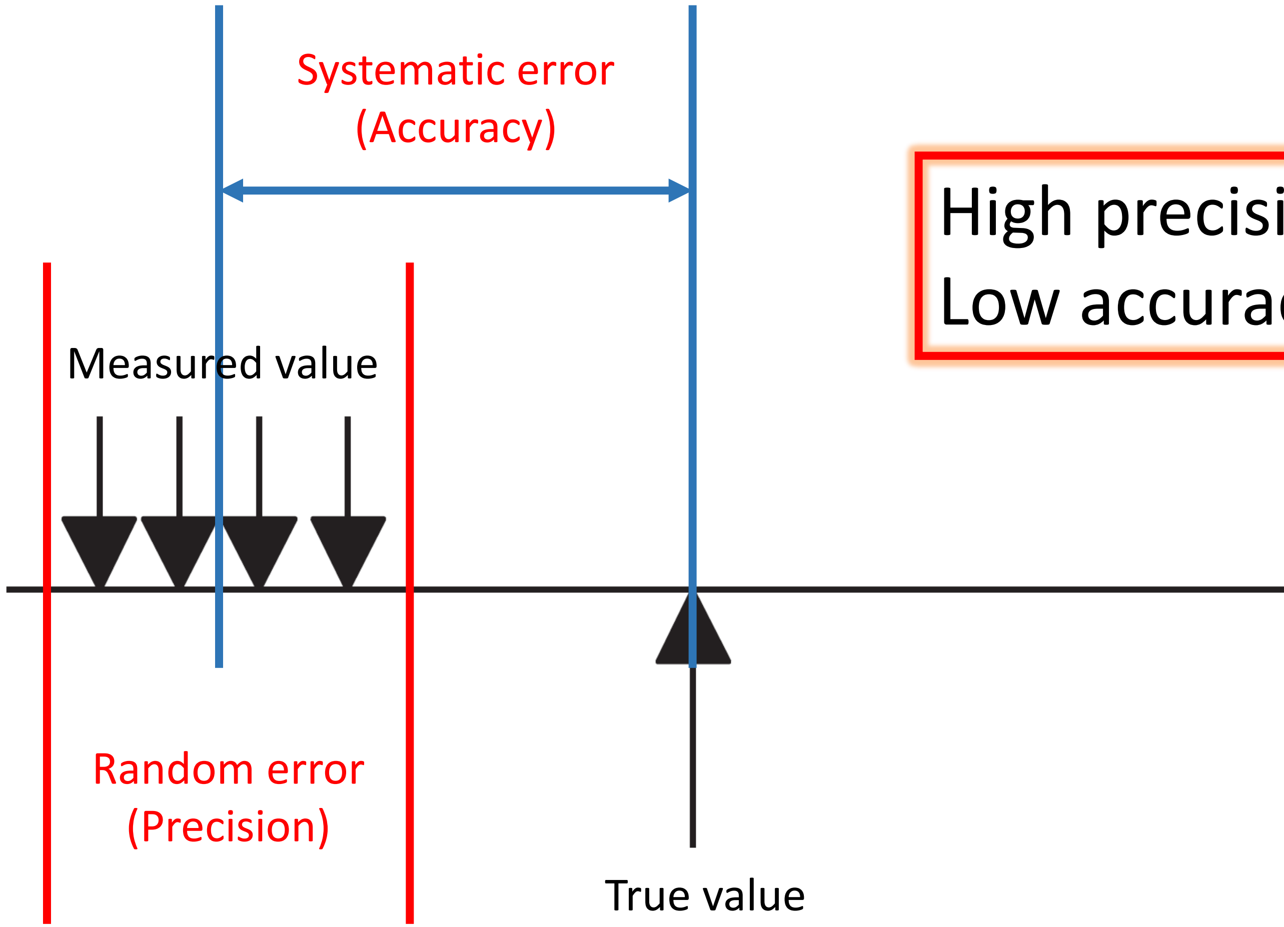
Accuracy:

- defined as the difference between the true value of the measurand and the measured value indicated by the instrument;
- determined by systematic error;
- usually expressed as a percentage of the full-scale deflection (FSD) of the transducer or system.

Precision:

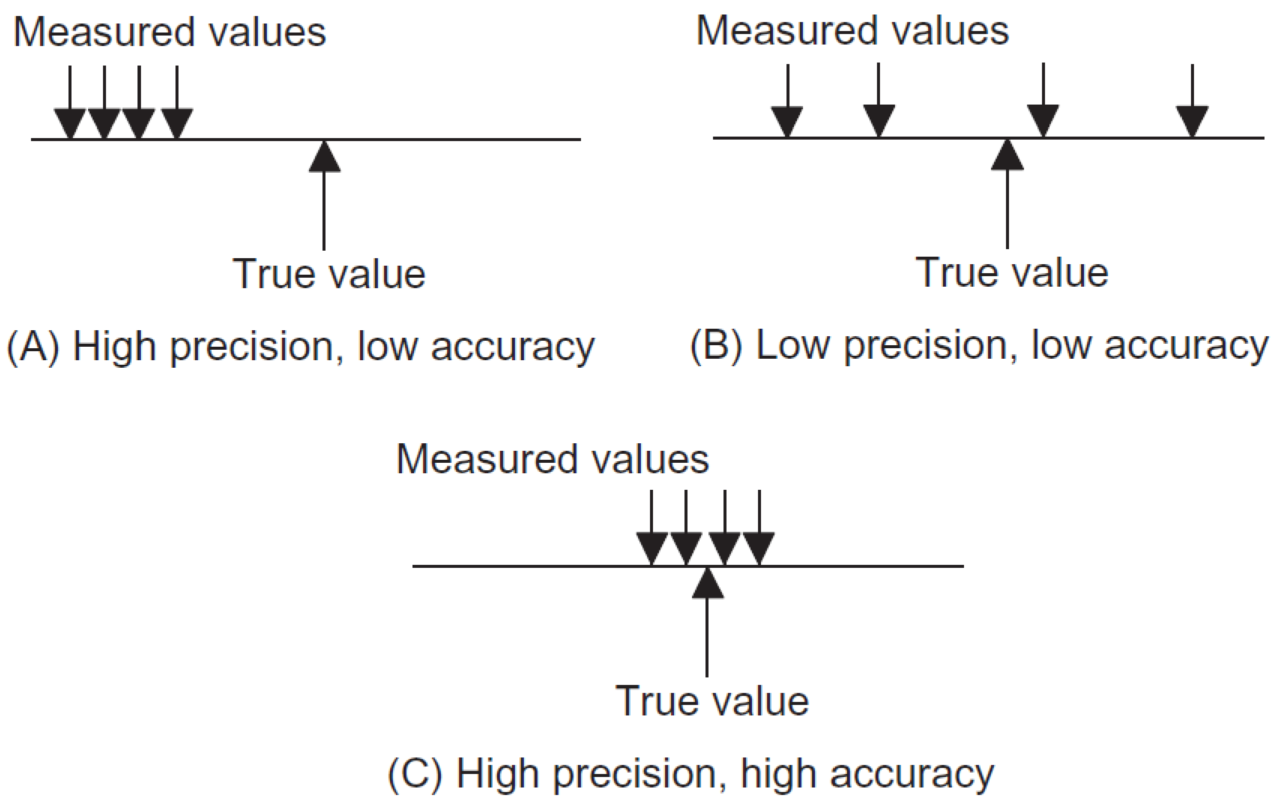
- a term that describes an instrument's degree of freedom from random errors;
- normally quantified by the standard deviation δ that indicates the width of the Gaussian distribution;
- The smaller the standard deviation, the more precise the measurement.

Target Analogy of Measurement – 1D

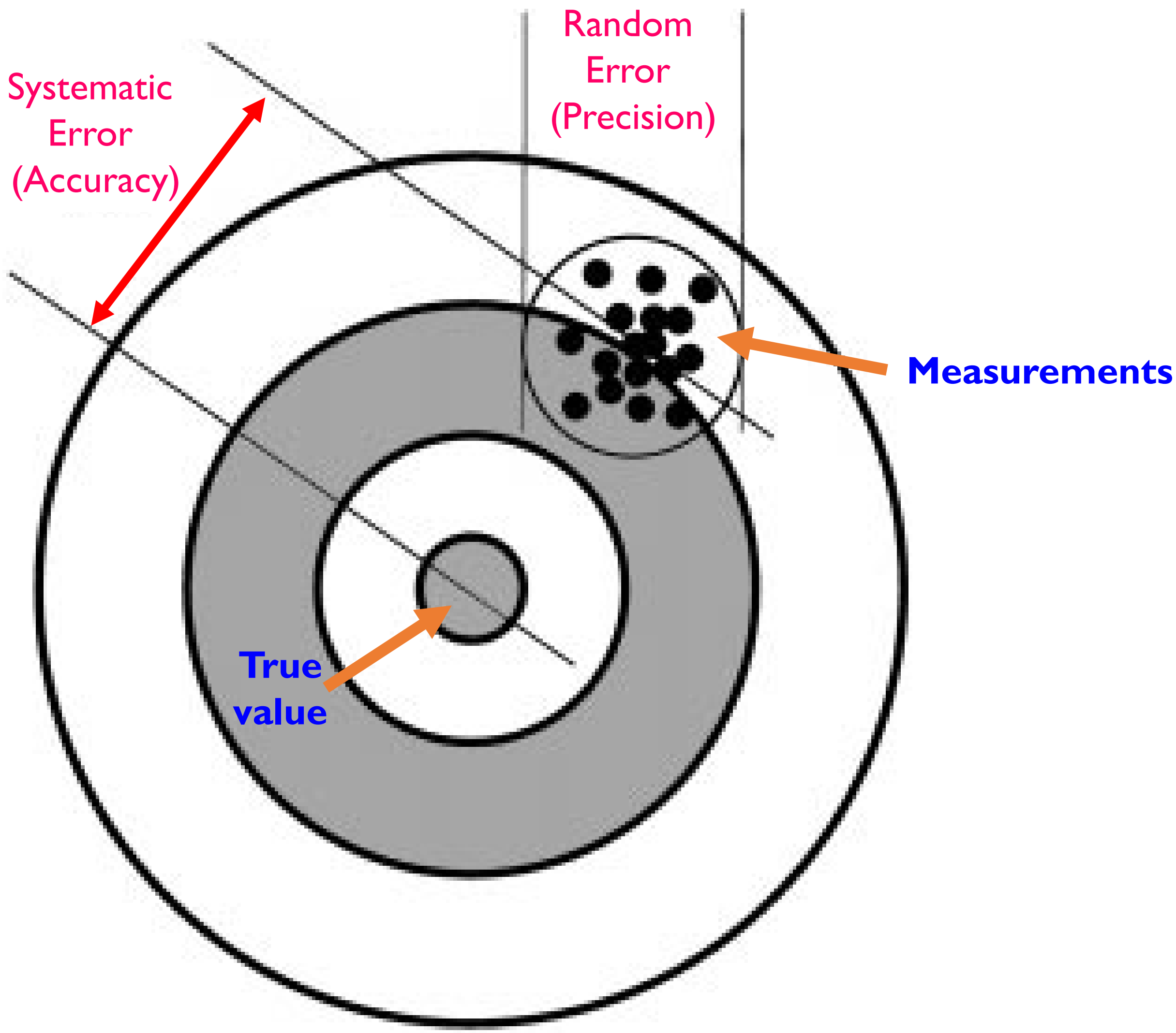


High precision
Low accuracy

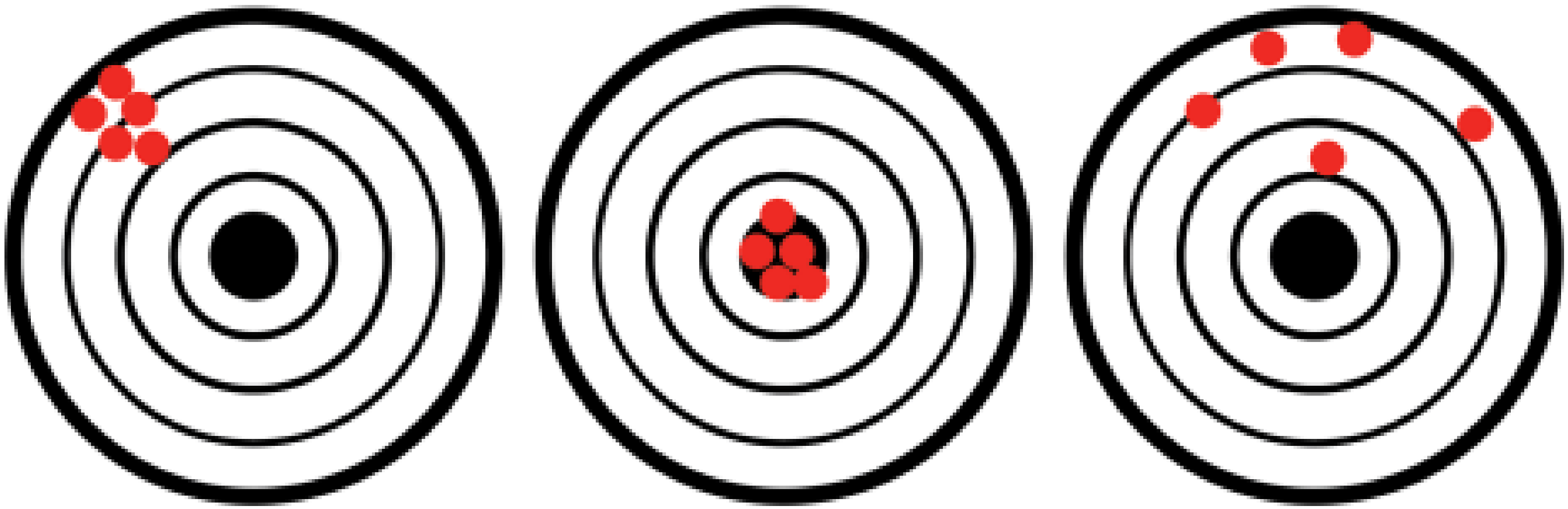
Accuracy vs. Precision – 1D



Target Analogy of Measurement – 2D



Accuracy vs. Precision – 2D



Poor accuracy but good precision

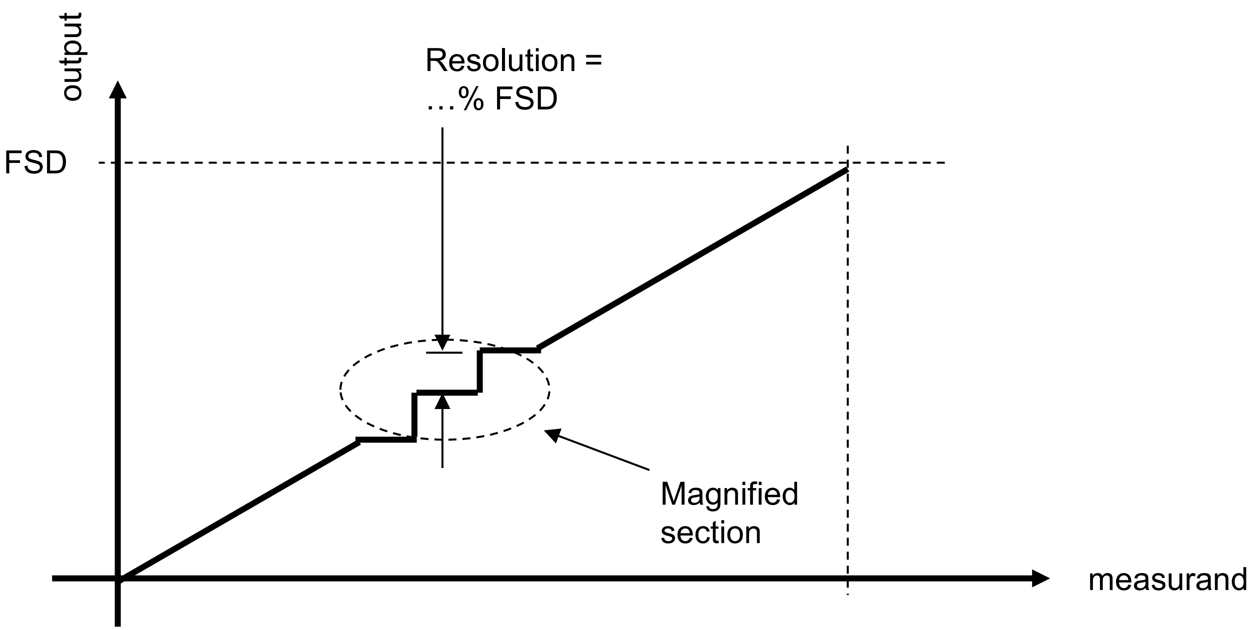
Good accuracy and good precision

Poor accuracy and poor precision

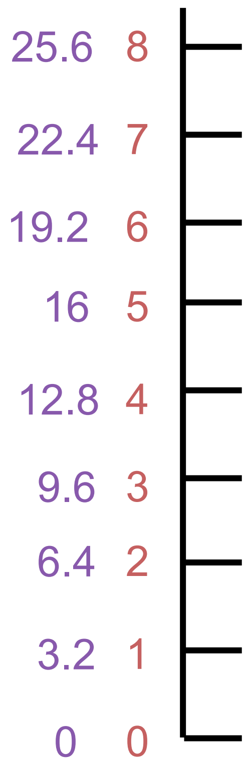
Resolution

Resolution:

- is the smallest change in the measurand that can be measured;
- the resulting maximum error is **half** the resolution of the measurement.



FSD: Full Scale Deflection



Unit (mm, ^oC, Volt etc.)

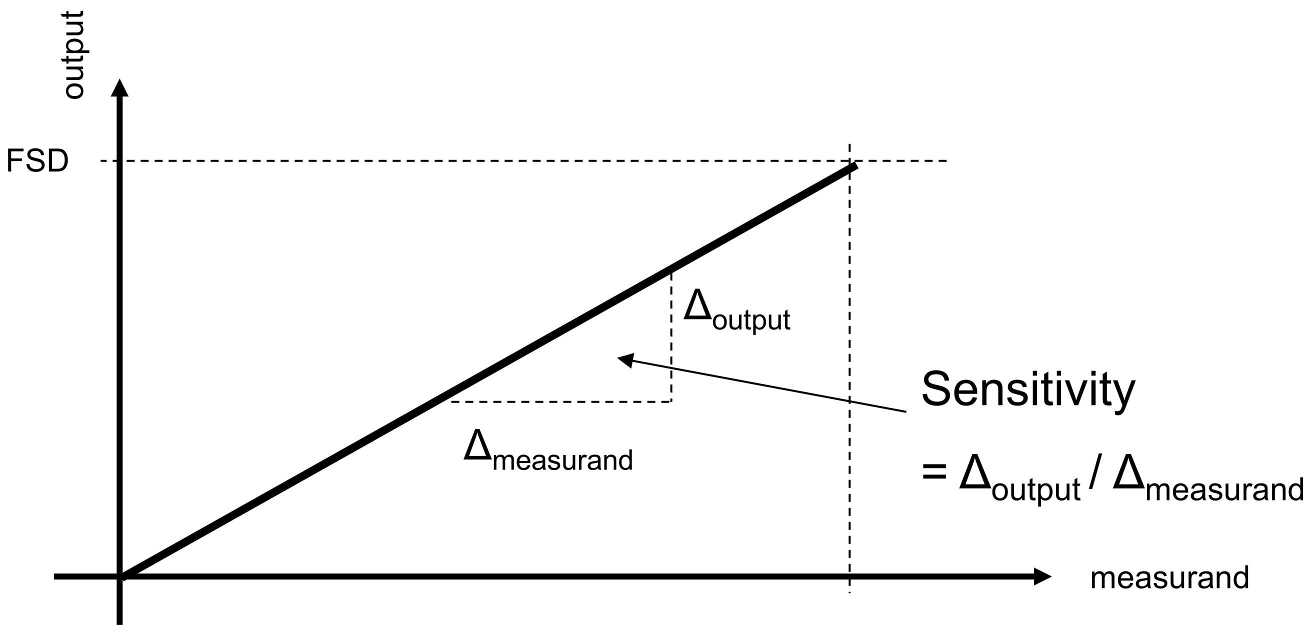
Resolution and Maximum Error

Resolution	True Value	Measurement	Error	
1	1.2	1	0.2	≤ 0.5
	3.6	4	0.4	
	7.5	7 or 8	0.5	
	…	…	…	
3.2	2.8	3.2	0.4	≤ 1.6
	17.5	16	1.5	
	24.8	25.6	0.8	
	…	…	…	

Sensitivity

Sensitivity:

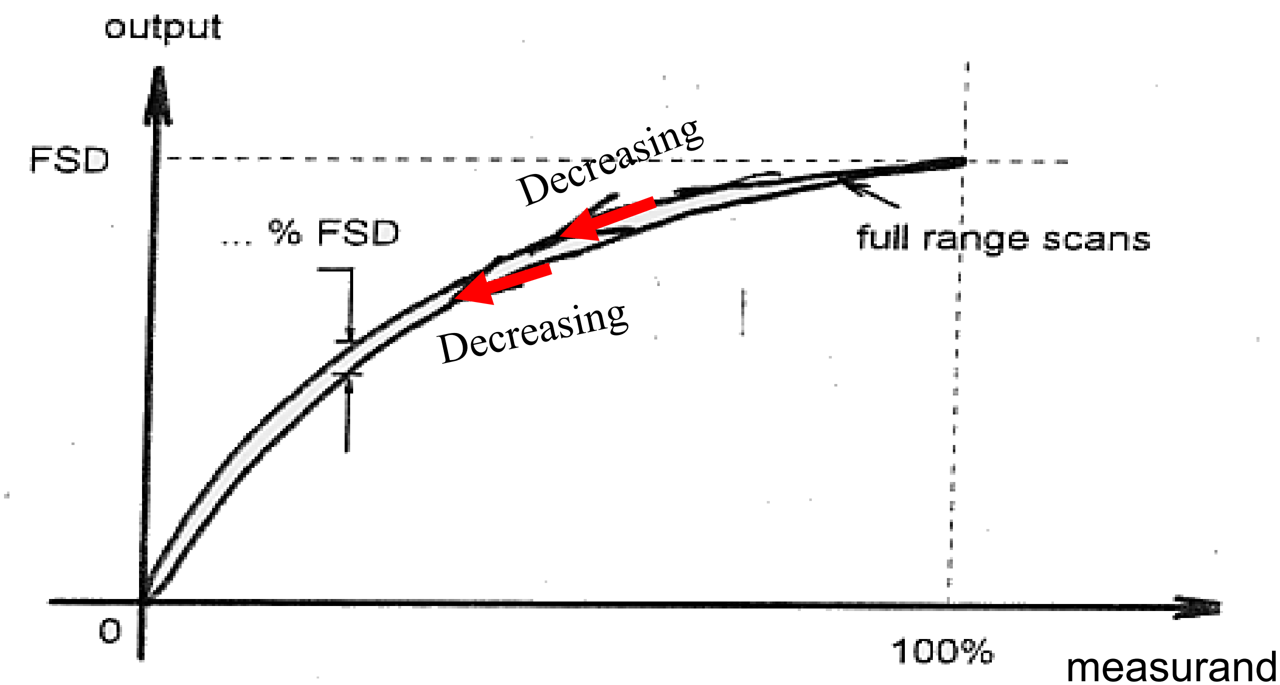
- is the slope of the output vs input (measurand) in the graph;
- note the difference between sensitivity and resolution.



Repeatability

Repeatability:

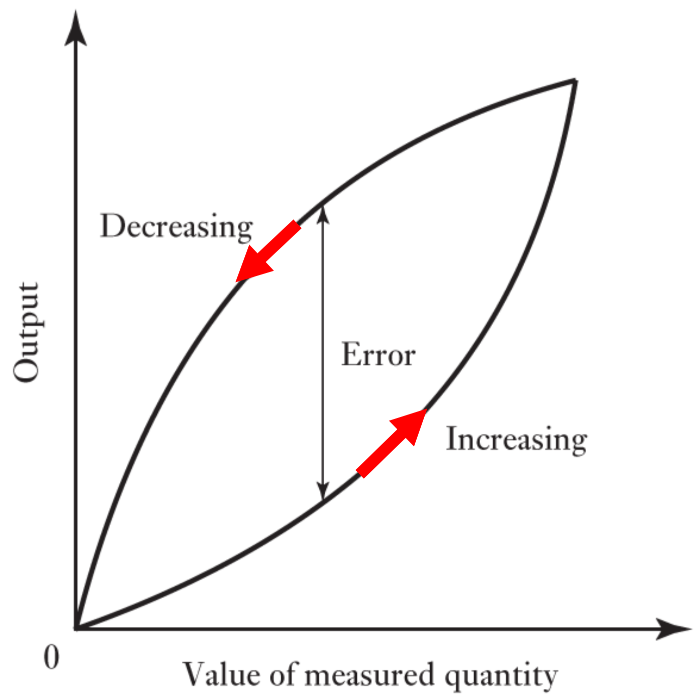
- relates to the maximum difference between any two output values at the same value of measurand taken during full range traverses of the measurand and approached from the same direction.



Hysteresis Error

Hysteresis error:

- the difference in transducer output obtained when any measurement point is approached from different directions during a full range scan of the transducer.



Example

Thermometer measuring the same temperature

- Reached by warming up to the measured temp;
- Reached by cooling down to the measure temp.

Non-linearity Error

Non-linearity error:

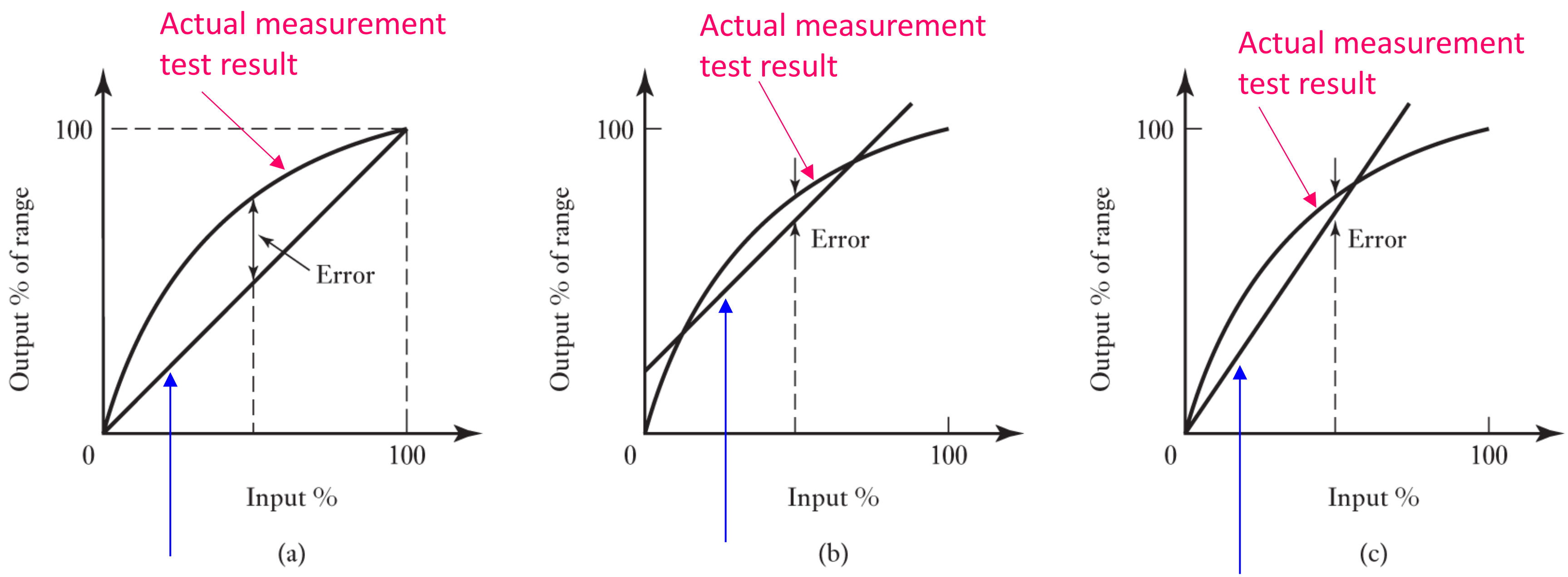
- For many transducers a linear relationship between the input and output is assumed over the working range, i.e., a graph of output plotted against input is assumed to give a straight line. Errors occur as a result of the assumption of linearity.

- Non-linearity is not necessarily a source of error at all. It only becomes one if the transducer is assumed to have a linear output (most are).

The error is defined as the **maximum difference** of the actual input-output curve from a straight line. Various methods are used for numerical expression of the nonlinearity error, depending on how to define the reference straight line.

Non-linearity Error

There are many ways to define non-linearity error, all depend on how to define the straight line.



(a) Straight line defined as the linear line connects the end points (**End-point nonlinearity**);

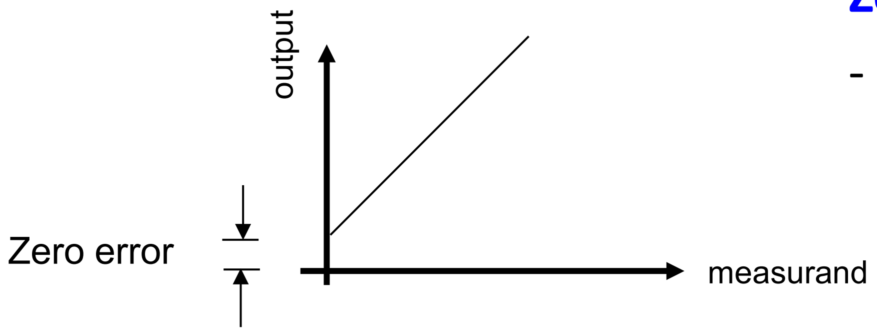
(b) Straight line defined as the best fit linear line based on all measurement data;

(c) Straight line defined as the best fit linear line based on all measurement data and also passes through the zero point.

In addition, analytical linear line: the straight line is the response that the transducer should have as given by theory.

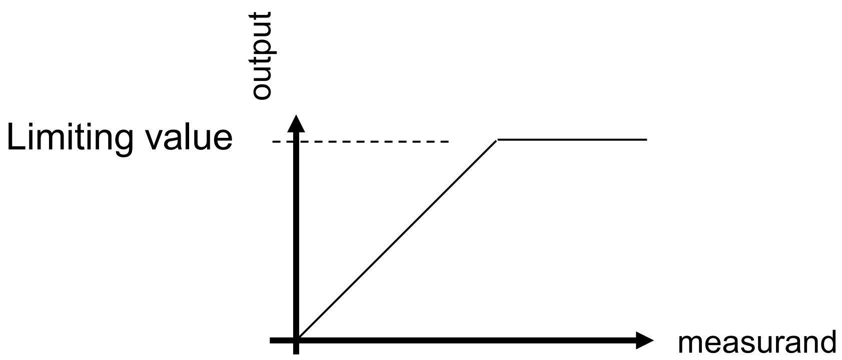
Inherent Error

Error resulted from the characteristic of the sensor



Zero error:

- self explanatory – may be specified as …% FSD or as a specified output value.



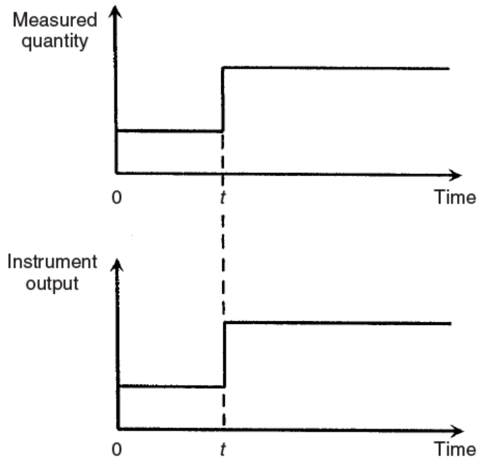
Limiting value:

- occurs due to the transducer being taken outside its calibrated operating range;
- often results in abrupt levelling off or saturation of the output.

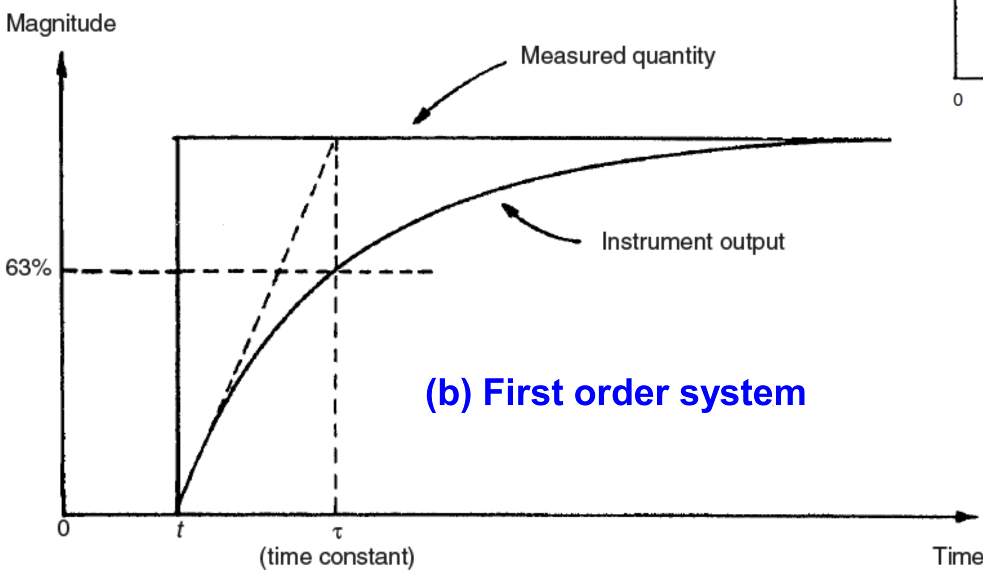
Outline

- Definition of Systems
- Instrumentation System: Definitions and Basic Concepts
- Overview of Control Systems
- Static Characteristics of Sensor Performance
- **Dynamic Characteristics of Sensor Performance**

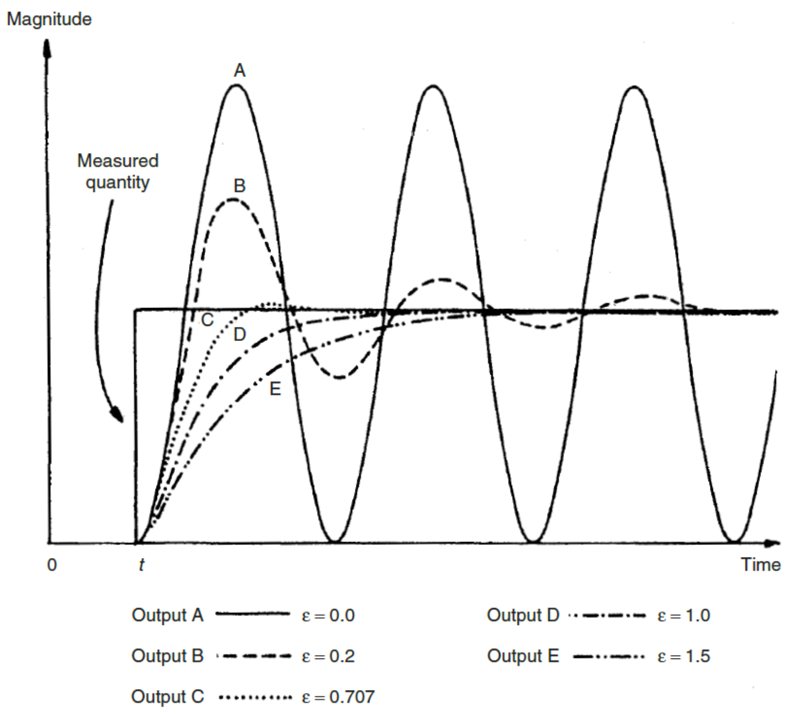
Dynamic Characteristics of Sensor Performance



(a) Zero order system

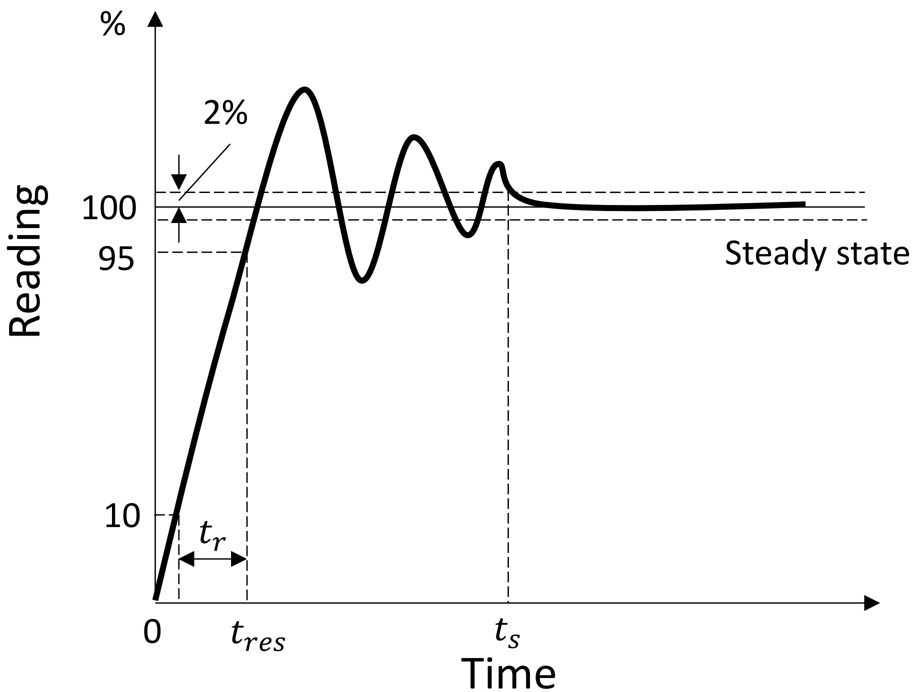


(b) First order system



(c) Second order system

Dynamic Characteristics of Sensor Performance



Settling time t_s:

- is the time taken for the output to settle to within some percentage, e.g., 2% of the steady-state value.

Response time t_{res}:

- is the time which elapses after the input to a system element is abruptly increased from zero to a constant value up to the point at which the system or element gives an output corresponding to some specified percentage, e.g. 95% of the value of the input.

Rise time t_r:

- is the time take for the output to rise to some specified percentage of the steady-state output, usually the duration of output to rise from 10% to 90% or 95% of the steady state.

System Design

When designing an instrumentation system it is necessary to:

1. **Choose the most appropriate measurement technique**
   - Should it be contact-less?
   - What signal processing is available?
   - What power sources are available?
2. **Choose the transducer**, e.g.
   - Is reliability important?
   - How accurate does it need to be?
   - Is weight important?
   - Is it to operate in a harsh environment?
3. **Design the signal conditioning as required**
4. **Whilst balancing overall cost against performance**

Quiz 1.1

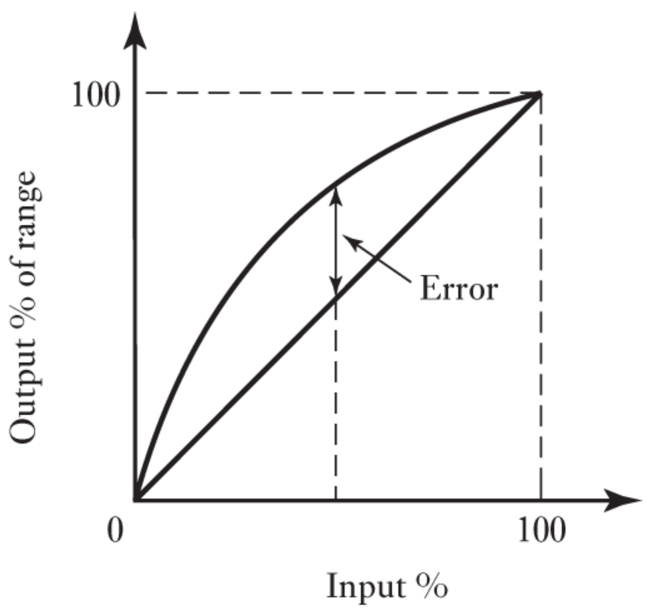
A pressure sensor has a range of 0 to 1,000 kPa and a non-linearity error of $\pm 0.15\%$ FSD and a hysteresis error of $\pm 0.05\%$ FSD. The error for a reading of 300kPa is

A. ± 0.3 kPa

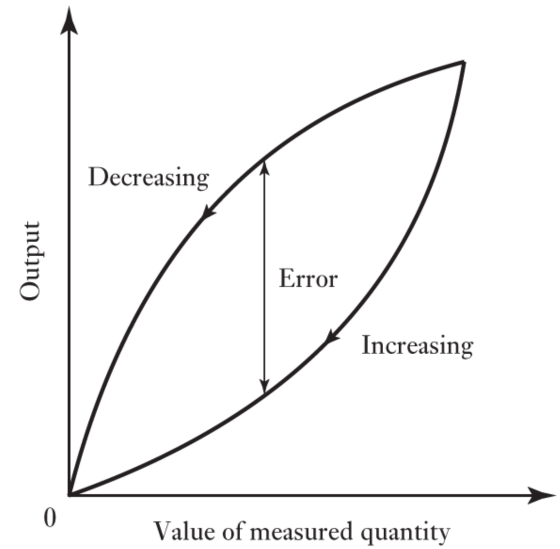
B. ± 0.6 kPa

C. ± 1.0 kPa

D. ± 2.0 kPa



non-linearity error



hysteresis error

Thank You !