Introduction to Control Systems Objectives

A control system consisting of interconnected components is designed to achieve a desired purpose.

To understand the purpose of a control system, it is useful to examine examples of control systems through the *course of history*. These early systems incorporated many of the same ideas of feedback that are in use *today*.

Modern control engineering practice includes the use of control design strategies for

- improving manufacturing processes,
- the efficiency of energy use,
- advanced automobile control, high-speed trains, robotics, biomedical, economics, social sciences, etc.

What is control? -1

Control system

- An interconnection of components that provide a desired system response
- Key enabling technology in all branches of engineering – *very interdisciplinary*
- Used whenever some quantity (e.g., **temperature**, **altitude**, **speed**, **concentration, pH**) must be made to behave in some desirable way <u>over time</u>
- Often exploits **feedback** to help regulate or control the system response

What is control? -2

Control system

- Compares actual behavior with desired behavior
- Takes corrective action based on the difference
- Subsystems and processes (plants) are assembled for the purpose of controlling the outputs of the process.
- **Examples:** Air Conditioner, elevator, antenna system, remote controlled robot, and so on.
- Why do we need to study control???
- **Example from social sci.:** student performance

input = study time, output = grade !!!

Basic Concepts

System – An interconnection of elements and devices for a desired purpose.

Control System – An interconnection of components forming a system configuration that will provide a desired response.

Process – The device, plant, or system under control. The input and output relationship represents the cause-and-effect relationship of the process.

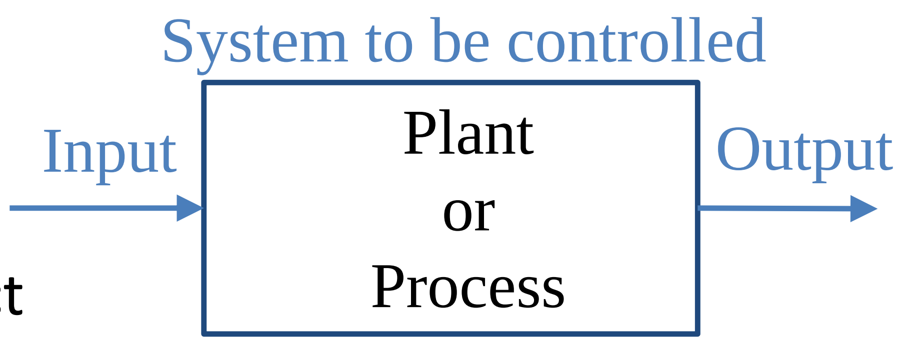
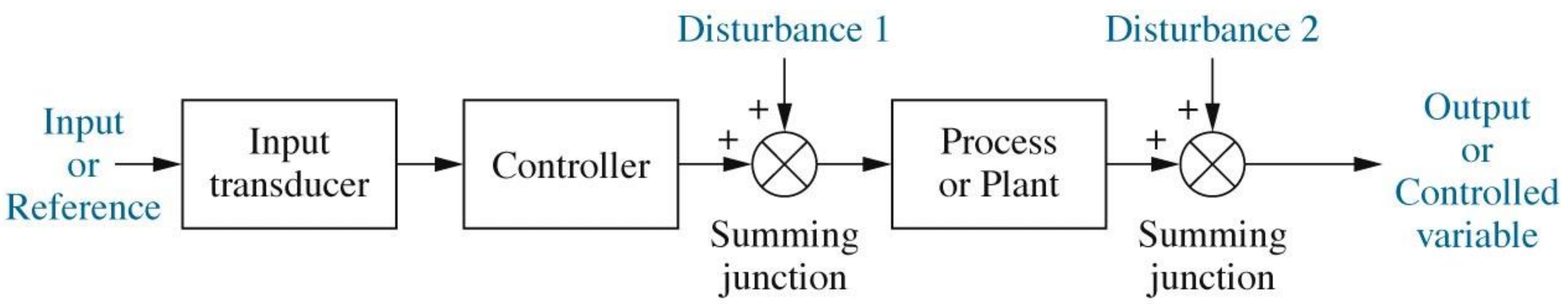
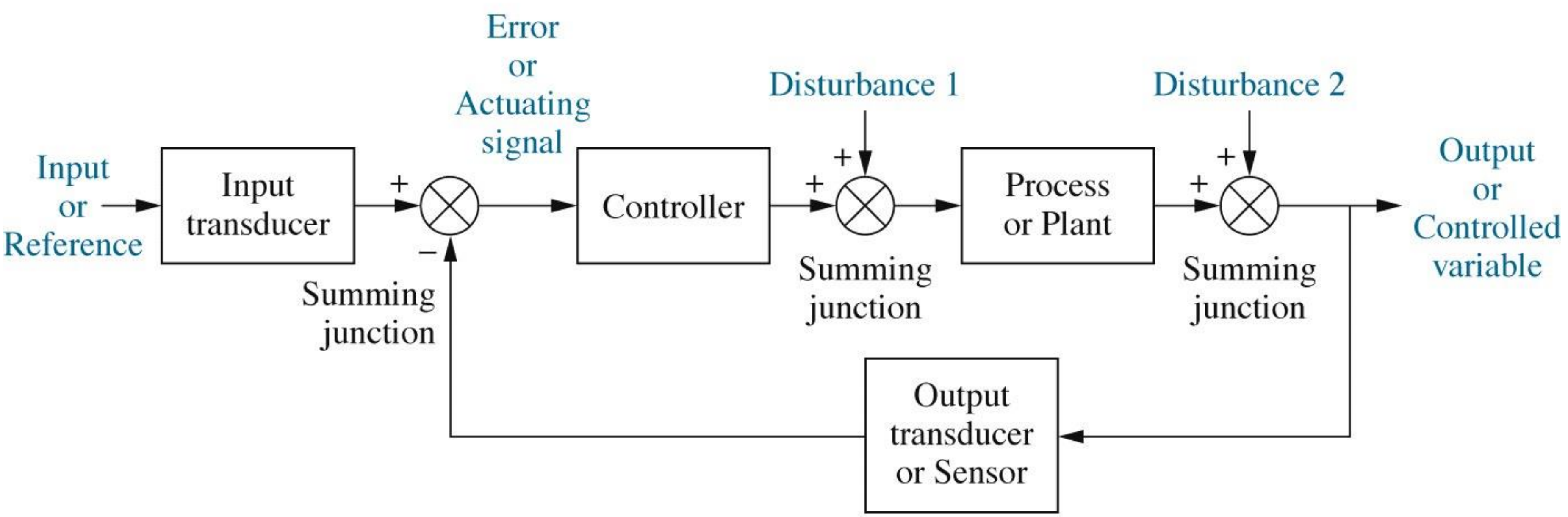


Figure 1.1

Open – Loop (*a*) vs. Closed Loop (*b*) -1



(*a*)



(*b*)

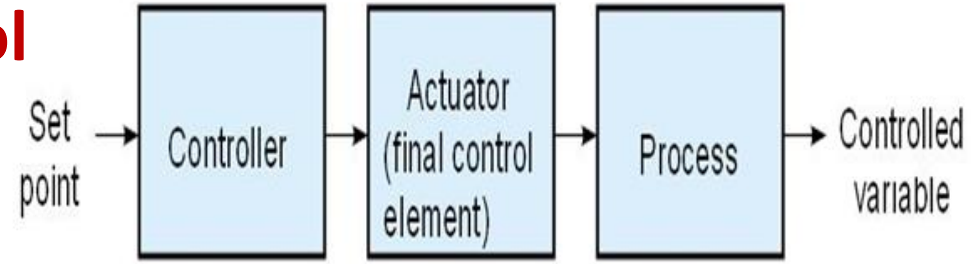
Figure 1.6

Open – Loop vs Closed Loop -2

O-L	C-L	Description
X		Cannot compensate for disturbances that affect the plant
	X	Higher accuracy and robustness to disturbances
X		Commanded by the input
	X	Commanded by the error via feedback
	X	Relatively more complex and expensive
	X	Improved performance and stability

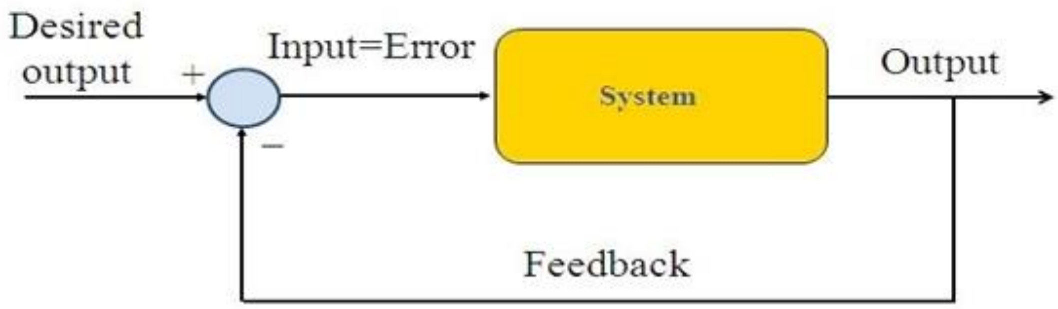
Two main types of control

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



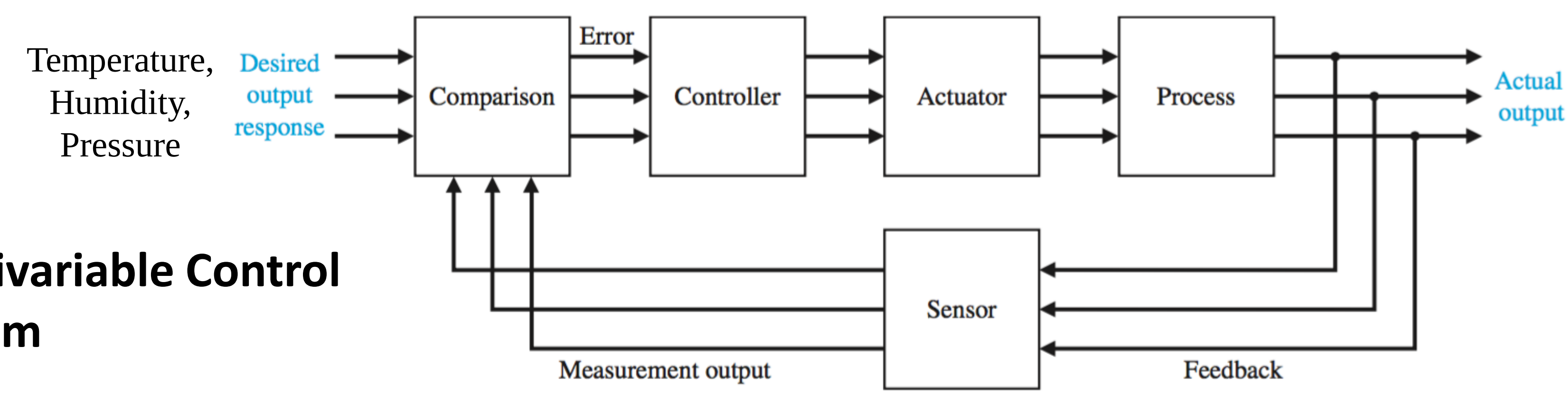
Open-loop control system (without feedback).

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



Closed-loop feedback control system (with feedback).

Multivariable Control System



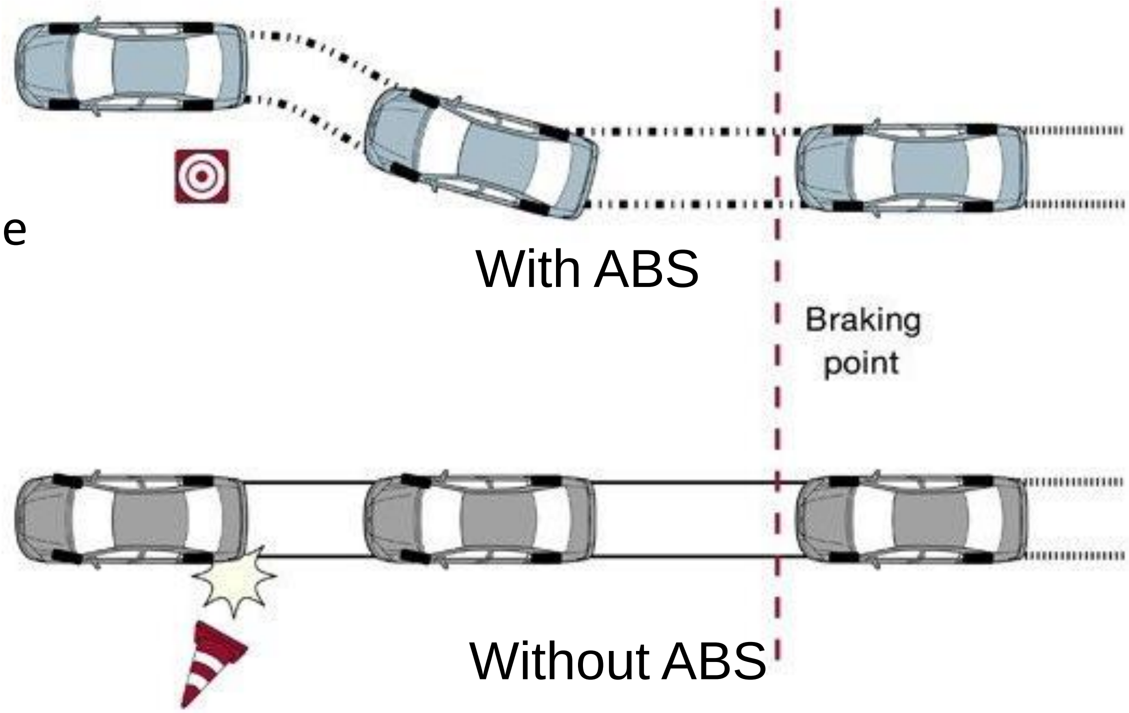
Multivariable Control System (with feedback)

Example Open-Loop and Closed-Loop Control Systems-1

Anti-lock braking system (ABS): ABS prevents the wheels from locking up, thus avoiding uncontrolled skidding of the vehicle and decreases the distance travelled without slipping.

Major components of a typical ABS system

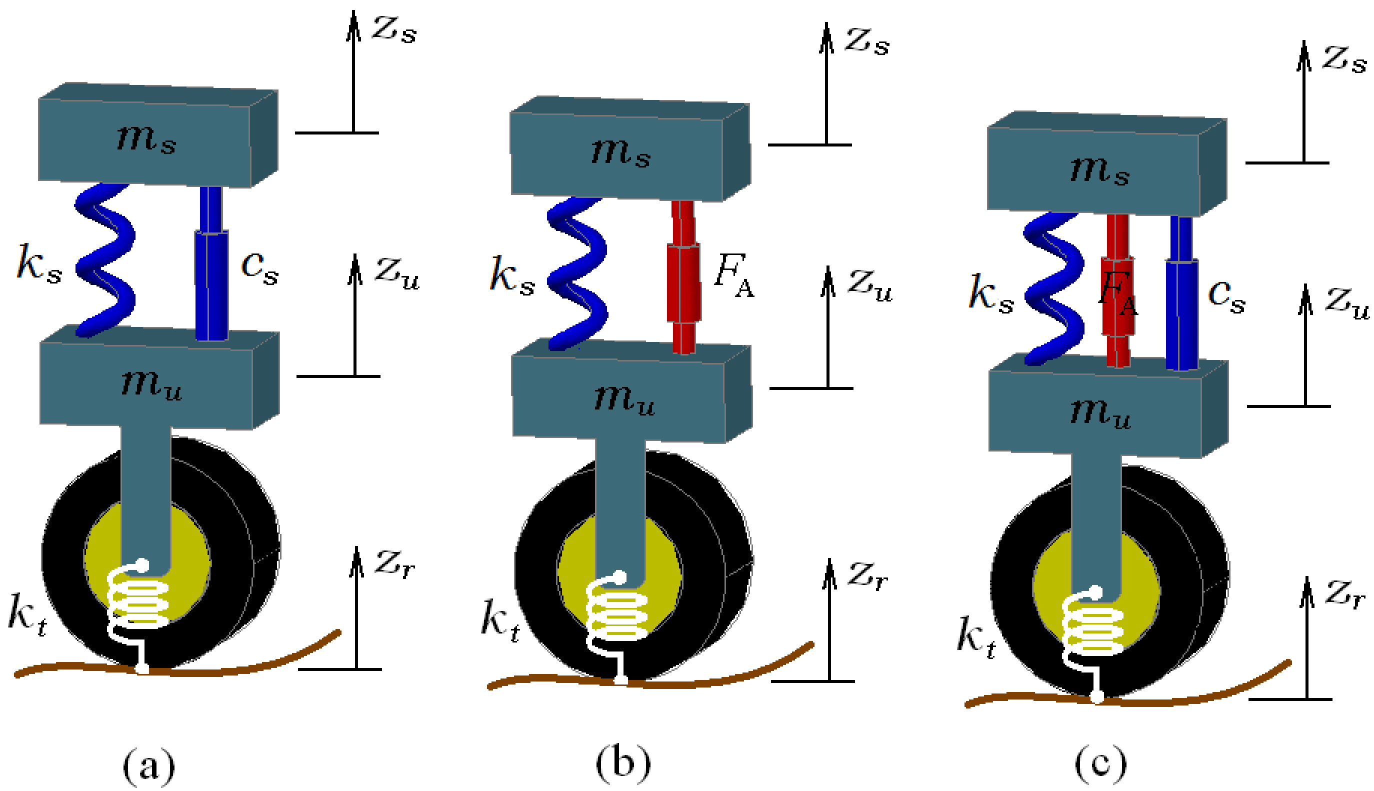
- **Four speed sensors** (one at each wheel)**:** monitors the speed of each wheel and determines the necessary acceleration and deceleration of the wheels.
- **Electronic Control Unit** (**ECU**): ECU receives, amplifies and filters the sensor signals for calculating the wheel rotational speed and acceleration. Then controls the brake pressure, according to the data that is analyzed.



- **Valves:** Regulate the air pressure to the brakes during the ABS action.
- **Hydraulic Control Unit:** Gets signals from the ECU to apply or release the brakes

Example Open-Loop and Closed-Loop Control Systems-1

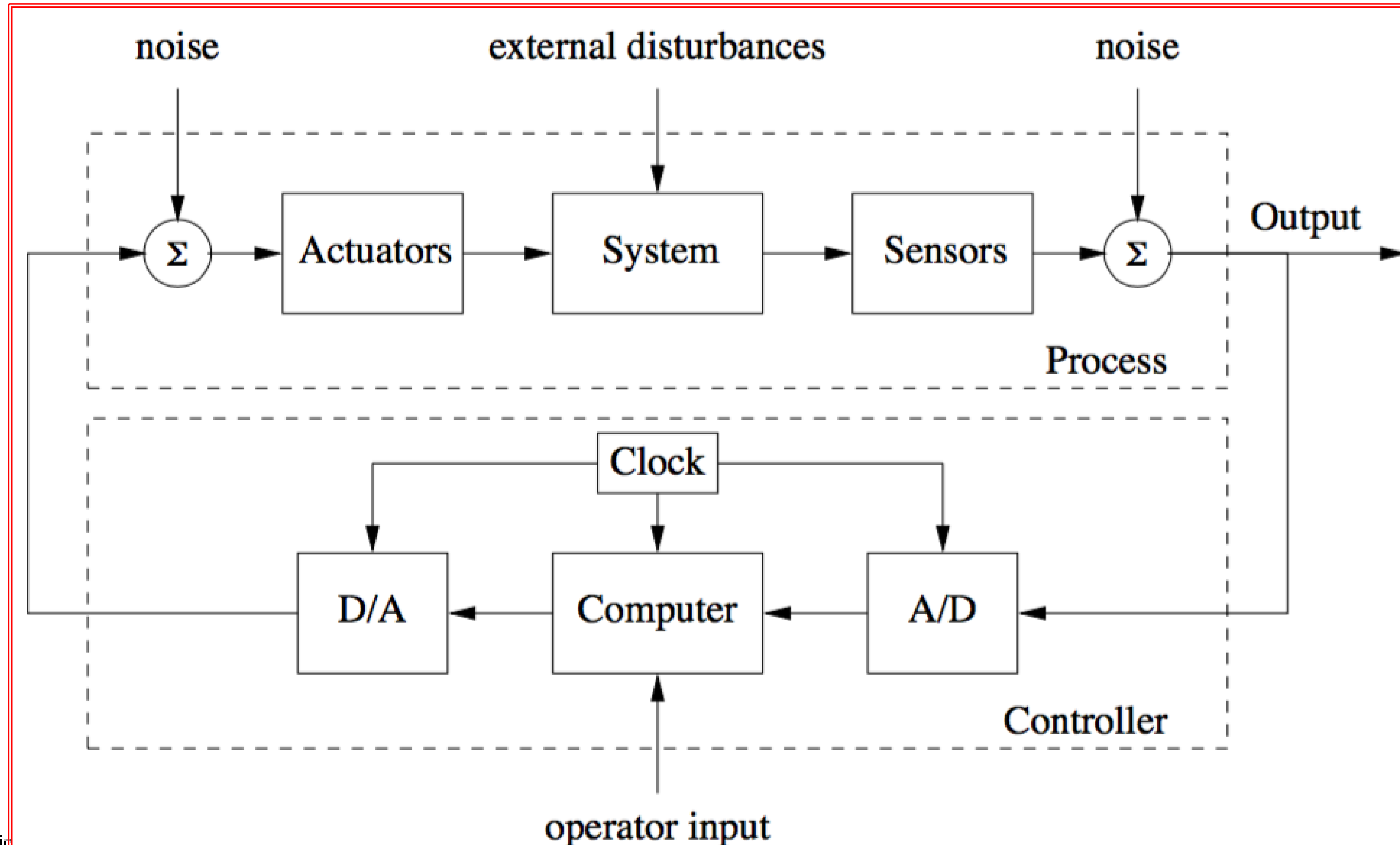
- **Vehicle suspension system:** a system that will absorb the energy of the vertically accelerated wheel, allowing the frame and body to ride undisturbed while the wheels follow bumps in the road.



Quarter-car suspension systems: (a) Passive Suspension System, (b) Active Electromagnetic Suspension System and (c) Active Hydraulic Suspension System.

Components of Computer-Controlled Systems

- The upper dashed box represents the process dynamics, which includes the sensors and actuators in addition to the dynamical system being controlled.
- The controller is shown in the lower dashed box. It consists of analog-to-digital (A/D) and digital-to-analog (D/A) converters and a computer that implements the control algorithm.
- A system clock controls the operation of the controller, synchronizing the A/D, D/A and computing processes. The operator input is fed to the computer as an external input.



Example O-L and C-L control systems

Consider the following four devices:




Which option most correctly describes those devices that are closed-loop systems?

A. Conventional toaster

B. Thermostat & ABS

C. Conventional toaster & ABS

D. Wheelchair-accessible push-button door opener

E. Conventional toaster, Thermostat, & Door opener

Examples from History

- Outstanding machines automated by means of water power
- Designed and manufactured by **Al-Jazari**, his full name is Badi' al-Zaman Abu-'l-'Izz Ibn Isma'il Ibn al-Razzaz al-Jazari بديع الزمان أَبُو اَلْعِزِ إسْماعِيلِ بْنُ الرِّزاز الجزري
- Al-Jazari lived in Diyar-Bakir and Mardin (in Turkey) during the late 12^{th} to early 13^{th} century (1136 – 1206)
- The book, *Knowledge of Ingenious Mechanical Devices* by Al-Jazari in 1206, consisted of plans of the machines, was presented to the Sultan of Artuqids (Artuklu)
- See - http://www.muslimheritage.com/article/al-jazari-mechanical-genius

The elephant clock invented by Al-Jazari

Examples from History…

- Al-Jazari built automated moving peacocks driven by hydropower,
- invented the earliest known automatic gates, which were driven by hydropower,
- created automatic doors as part of one of his elaborate water clocks,
- invented water wheels with cams on their axle used to operate automata,
- **His example automated machines:**
  - ✓ Drink-serving waitress
  - ✓ Hand-washing automaton with flush mechanism
  - ✓ Peacock fountain with automated servants
  - ✓ Musical robot band
  - ✓ Clock

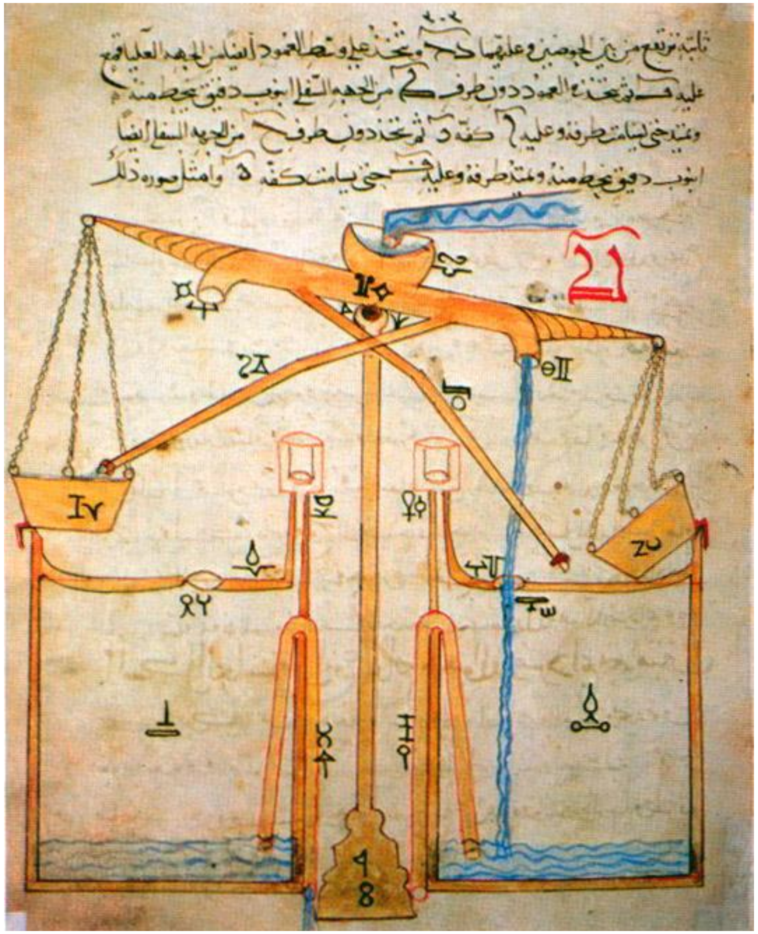
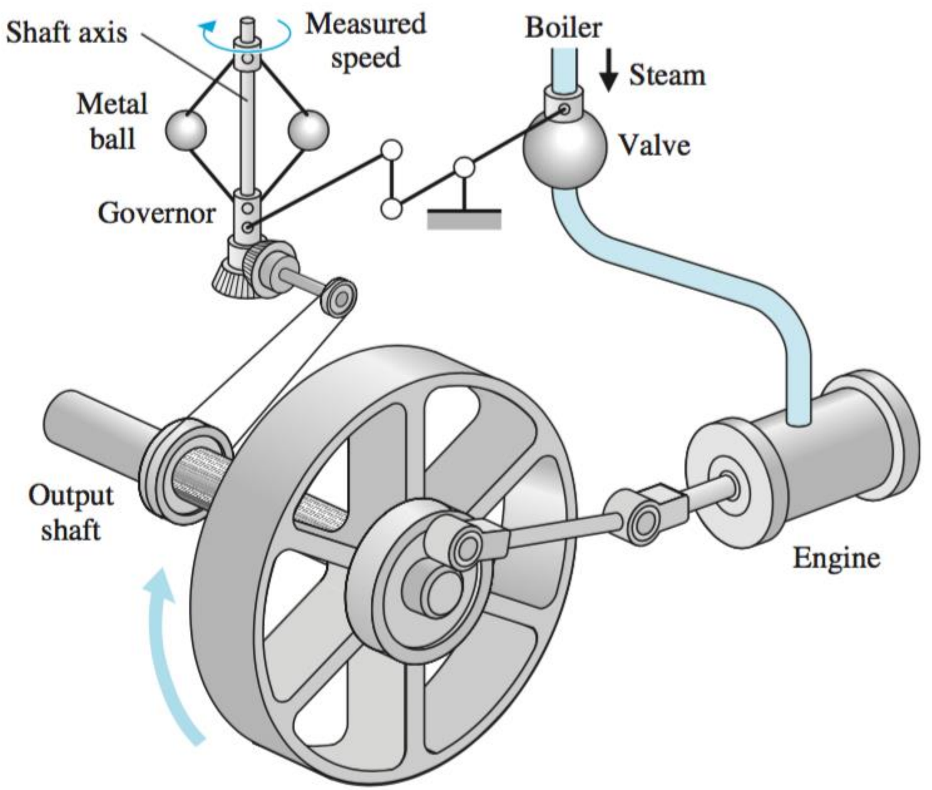


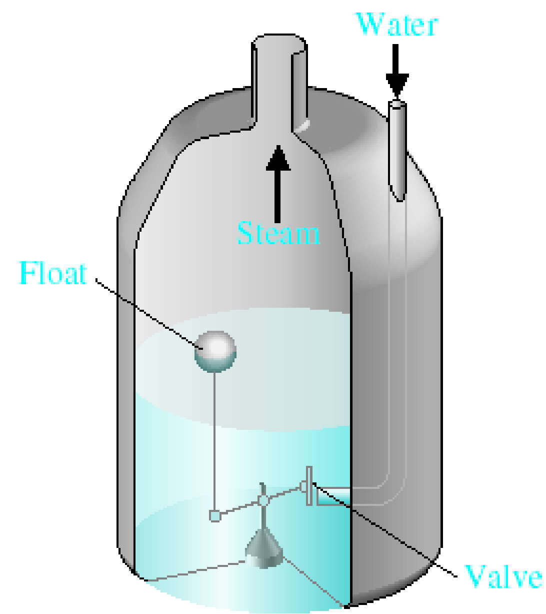
Diagram of a hydropowered perpetual flute from *The Book of Knowledge of Ingenious Mechanical Devices* by Al-Jazari in 1206. See: https://en.0wikipedia.org/

Examples from History…

- Greece (BC) – Float regulator mechanism
- Holland (16th Century)– Temperature regulator
- Watt's Fly-ball Governor (18th century, UK) (below left)
- Water-level float regulator (I. Polzunov, 1765, Russia) (below right)



Watt's fly-ball governor.



Water-level float regulator

History - milestones

18th Century James Watt's centrifugal governor for the speed control of a steam engine.

1920s Minorsky worked on automatic controllers for steering ships.

1930s Nyquist developed a method for analyzing the stability of controlled systems

1940s Frequency response methods made it possible to design linear closed-loop control systems

1950s Root-locus method due to Evans was fully developed

1960s State space methods, optimal control, adaptive control and

1980s Learning controls are begun to investigated and developed.

Present and on-going research fields. Recent application of modern control theory includes such non-engineering systems such as biological, biomedical, economic and socio-economic systems. Digitalization in Factories, Industry 4.0, Internet of Things…

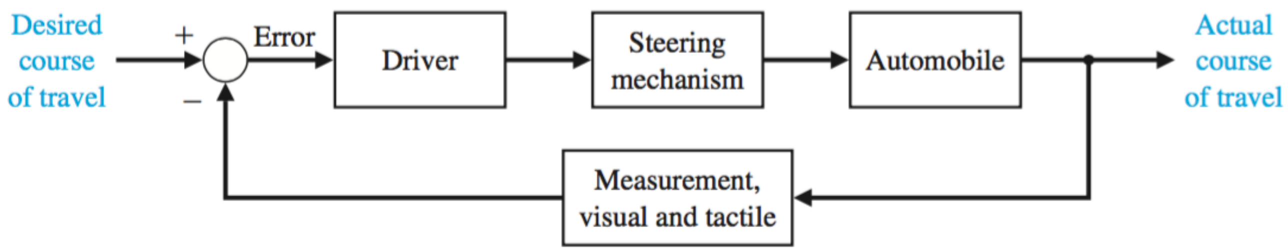
History with more mile stones (from R. Dorf's book)

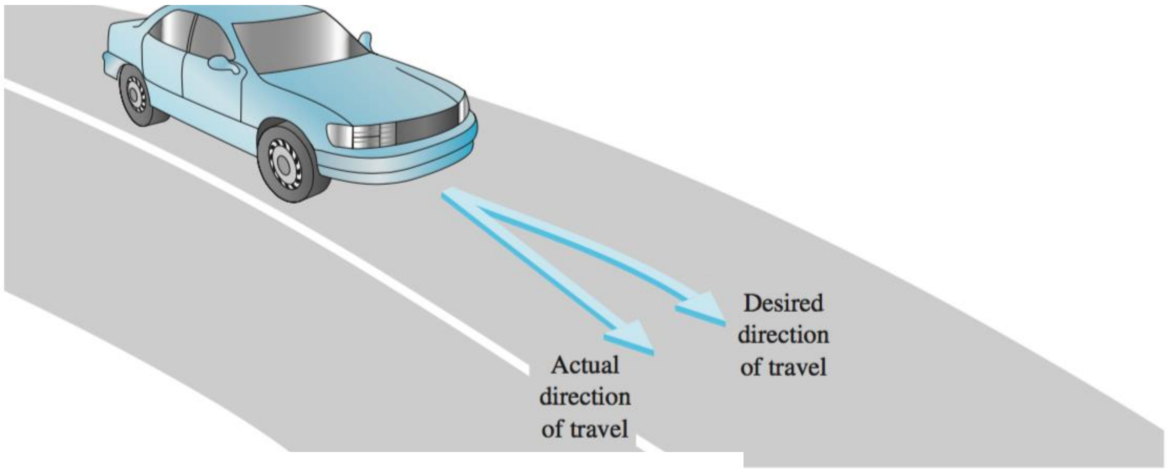
Year	Event
1769	James Watt's steam engine and governor developed.
1868	J. C. Maxwell formulates a mathematical model for a governor control of a steam engine.
1913	Henry Ford's mechanized assembly machine introduced for automobile production.
1927	H. S. Black conceives of the negative feedback amplifier and H. W. Bode analyzes feedback amplifiers.
1932	H. Nyquist develops a method for analyzing the stability of systems.
1941	Creation of first antiaircraft gun with active control.
1952	Numerical control (NC) developed at Massachusetts Institute of Technology for control of machine-tool axes.
1954	George Devol develops "programmed article transfer," considered to be the first industrial robot design.
1957	Sputnik launches the space age leading, in time, to miniaturization of computers and advances in automatic control theory.
1960	First Unimate robot introduced, based on Devol's designs. Unimate installed in 1961 for tending die-casting machines.

1970	State-variable models and optimal control developed.
1980	Robust control system design widely studied.
1983	Introduction of the personal computer (and control design software soon thereafter) brought the tools of design to the engineer's desktop.
1990	The government ARPANET (the first network to use the Internet Protocol) was decommissioned and private connections to the Internet by commercial companies rapidly spread.
1994	Feedback control widely used in automobiles. Reliable, robust systems demanded in manufacturing.
1995	The Global Positioning System (GPS) was operational providing positioning, navigation, and timing services worldwide.
1997	First ever autonomous rover vehicle, Sojourner, explores the Martian surface.
2007	The Orbital Express mission performed the first autonomous space rendezvous and docking.
2011	The NASA Robonaut R2 became the first US-built robot on the International Space Station designed to assist with crew extravehicular activities (EVAs).
2013	For the first time, a vehicle—known as BRAiVE and designed at the U of Parma, Italy—moved autonomously on a mixed traffic route open to public traffic without a passenger in the driver seat.
2014	Internet of Things (IoT) enabled by convergence of key systems including embedded systems, wireless sensor net's, control systems, and automation.

Examples of Modern Control Systems

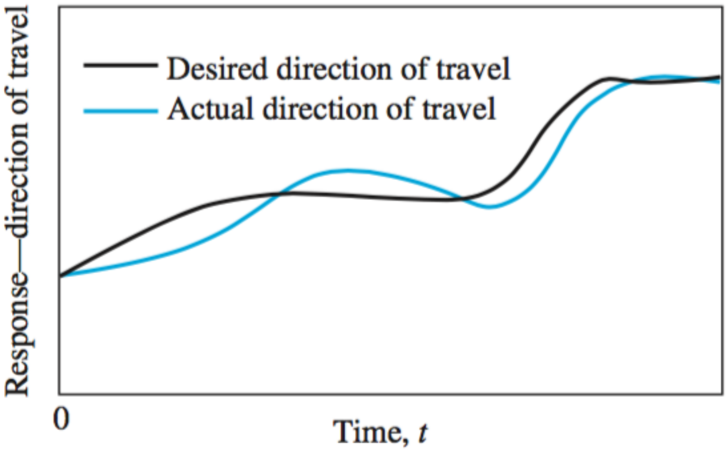
Automobile steering control system.



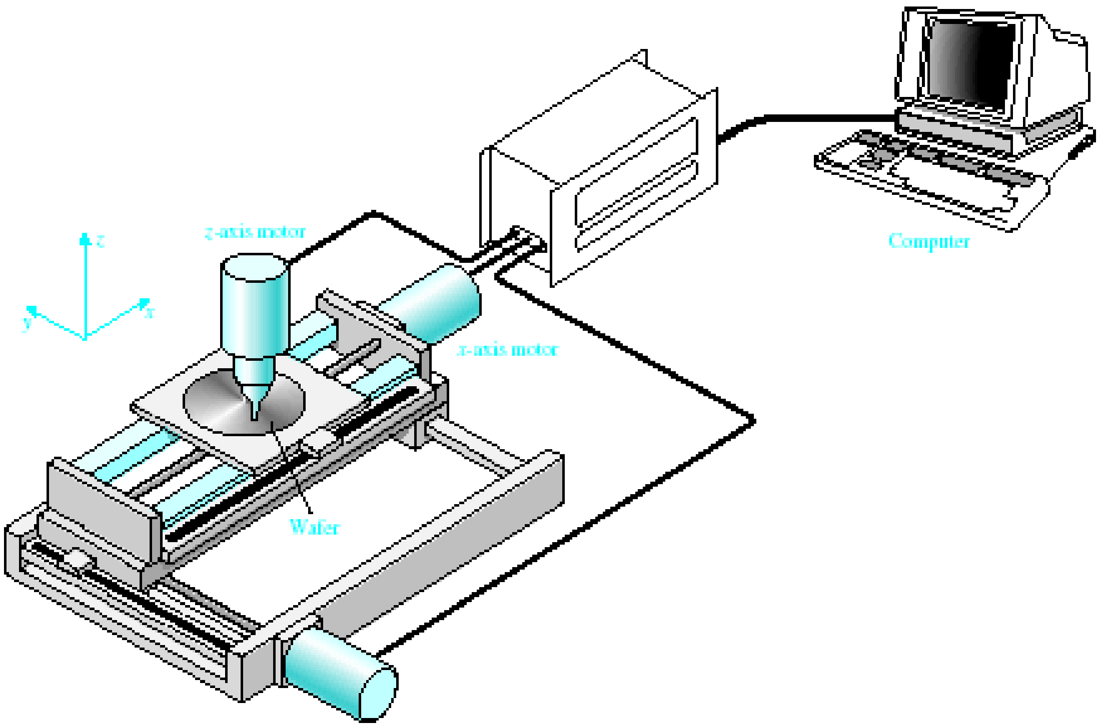


The driver uses the difference between the actual and the desired direction of travel to generate a controlled adjustment of the steering wheel.

Typical direction-of-travel response.

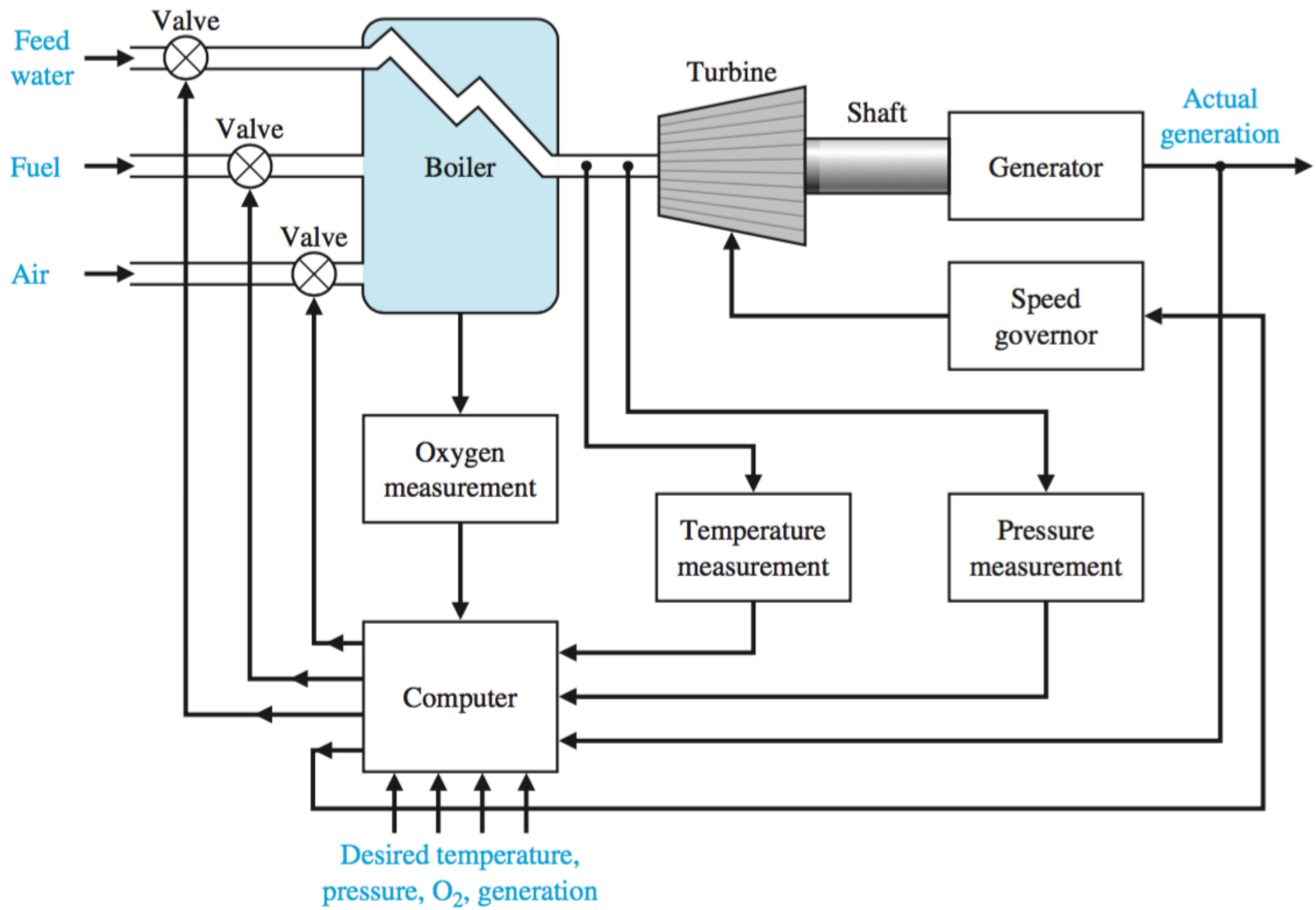


Examples of Modern Control Systems



A three-axis control system for inspecting individual semiconductor wafers with a highly sensitive camera.

Examples of Modern Control Systems



Coordinated control system for a boiler–generator.

Military aerospace systems

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

(b) The X-45 (UCAV) unmanned aerial vehicle is capable of autonomous flight, using inertial measurement sensors and the global positioning system (GPS) to monitor its position relative to a desired trajectory.

Photographs courtesy of NASA Dryden Flight Research Center.

(a)

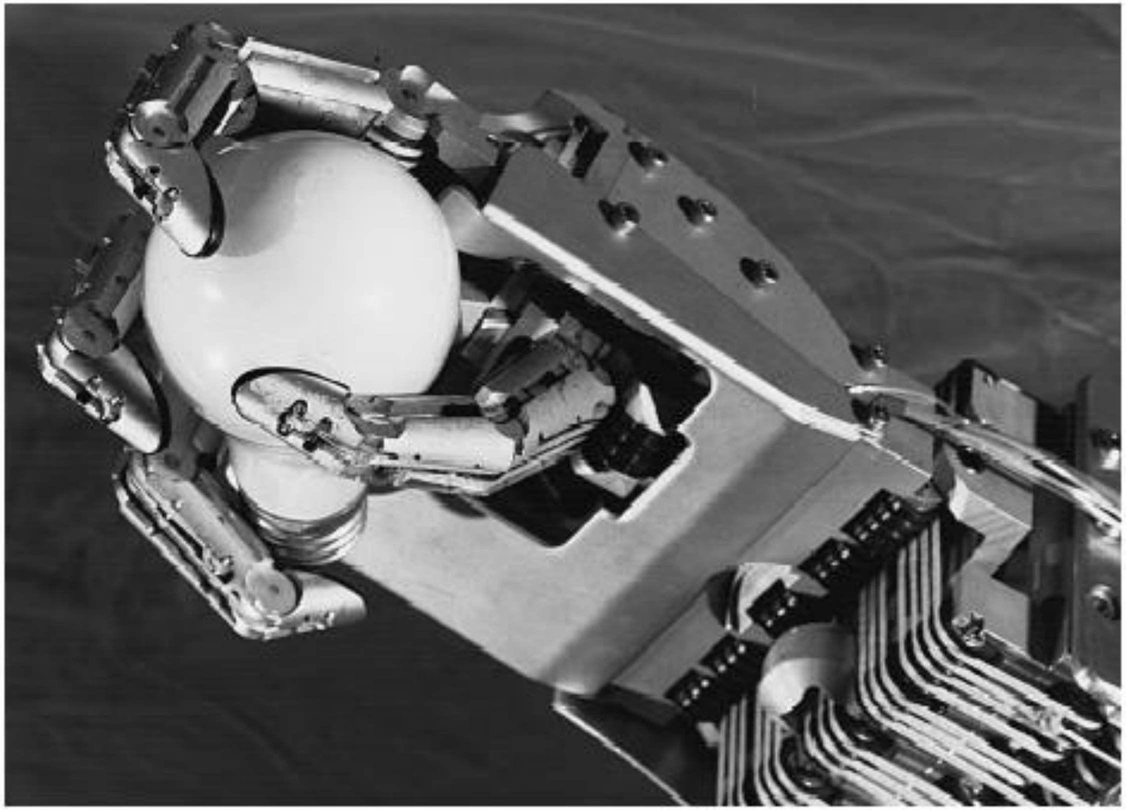
(b)

Examples of Modern Control Systems

ASIMO is a bipedal humanoid robot Honda has been developing with a goal to develop robots that will coexist with and be useful to people. The first version of ASIMO was introduced in November 2000. The latest version of ASIMO, introduced in November 2011, features not only high physical capability that allows it to make not only various moves such as running, going up and down stairs and kicking a ball, but also an ability to recognize faces/voices of people and take action accordingly and autonomous behavior control such as avoiding obstacles depending on the situation of the surroundings.

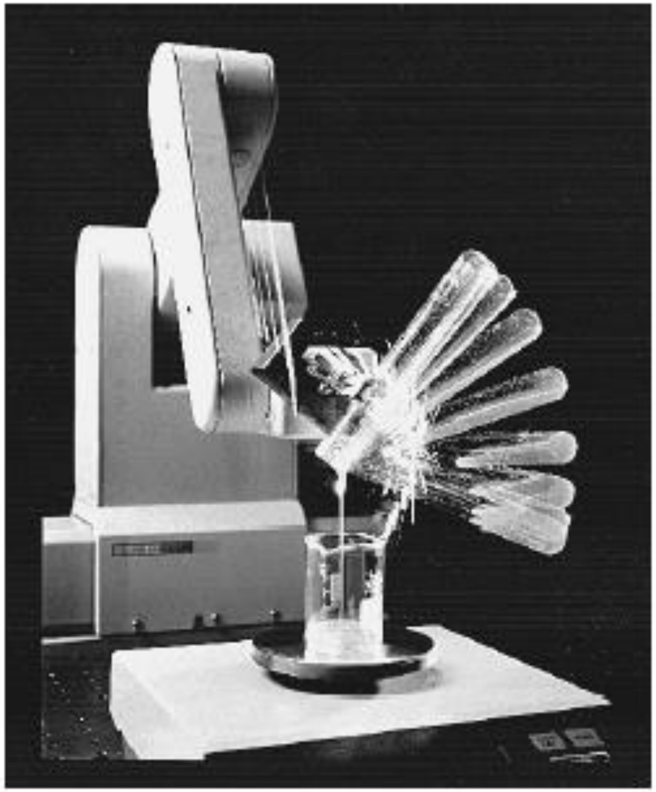
The UNI-CUB β is a new personal mobility device that features Honda's proprietary balance control technology which originates from Honda research into humanoid robots and the omnidirectional driving wheel system (Honda Omni Traction Drive System: Multiple small-diameter wheels are connected in-line to form one large-diameter wheel, which makes it possible to move forward, backward, laterally and diagonally).

Examples of Modern Control Systems



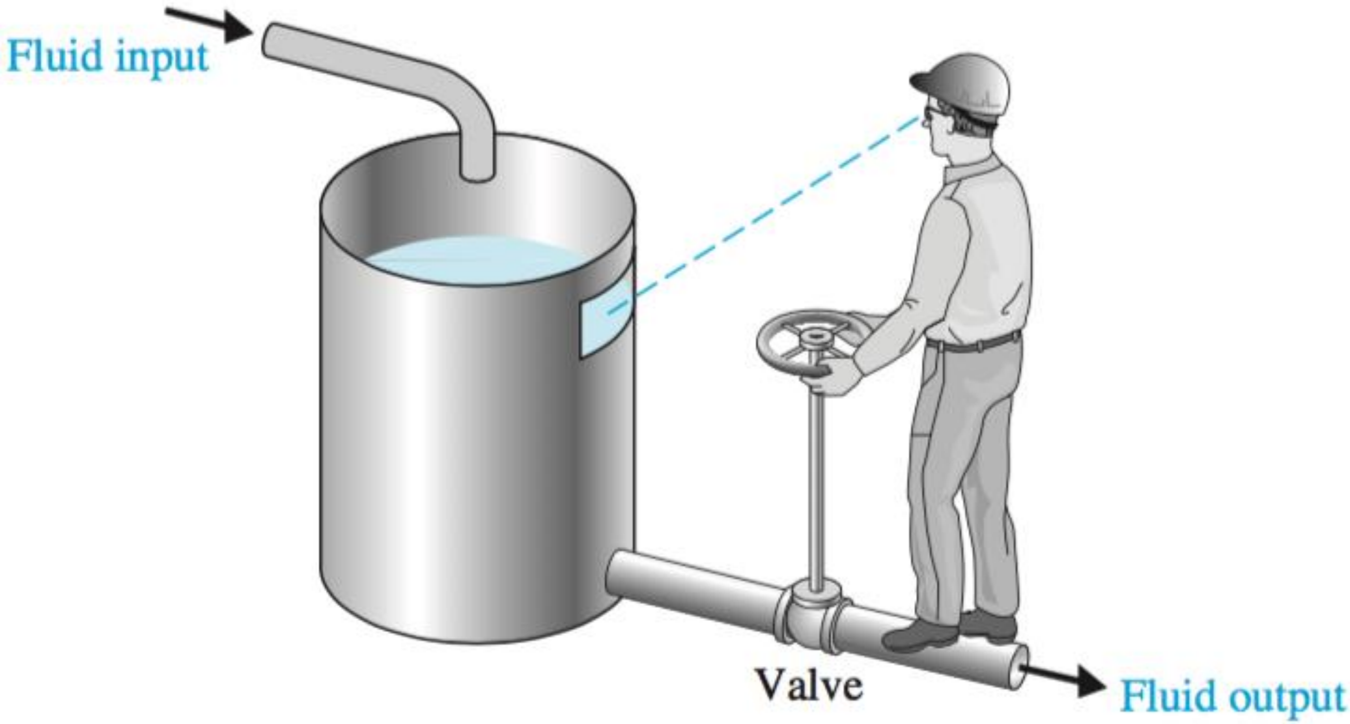
The Utah/MIT Dextrous Robotic Hand: A dextrous robotic hand having 18 degrees of freedom, developed as a research tool by the Center for Engineering Design at the University of Utah and the Artificial Intelligence Laboratory at MIT. It is controlled by five Motorola 68000 microprocessors and actuated by 36 high-performance electropneumatic actuators via high-strength polymeric tendons. The hand has three fingers and a thumb. It uses touch sensors and tendons for control. (Photograph by Michael Milochik. Courtesy of University of Utah.)

Examples of Modern Control Systems



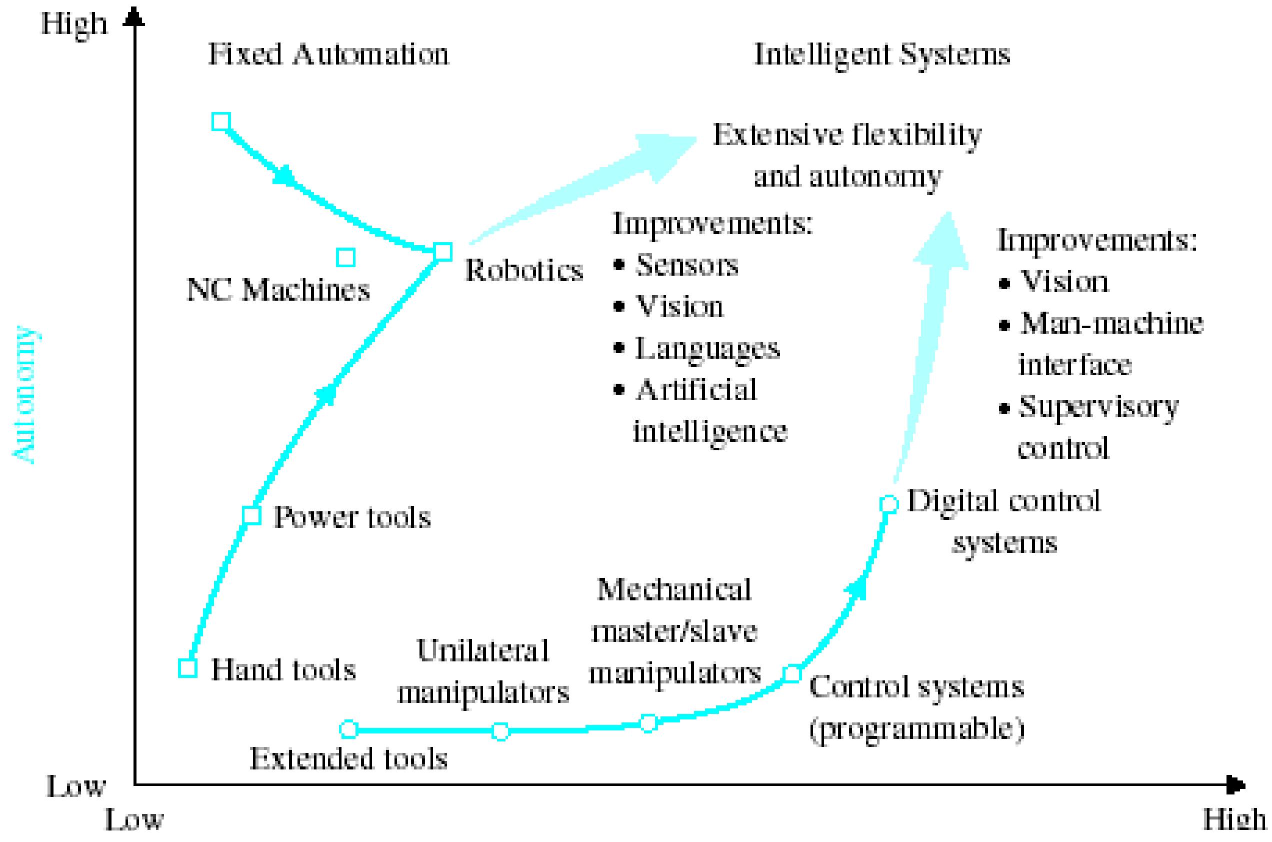
A laboratory robot used for sample preparation. The robot manipulates small objects, such as test tubes, and probes in and out of tight places at relatively high speeds [41]. (© Copyright 1993 Hewlett-Packard Company. Reproduced with permission.)

Example of a Manual Control System



Human-in-the-loop control: A manual control system for regulating the level of fluid in a tank by adjusting the output valve. The operator views the level of fluid through a port in the side of the tank.

The Future of Control Systems



Future evolution of control systems and robotics.

Control System Design Process

1. Establish the control goals
2. Identify the variable to control
3. Write the specifications for the variables
4. Establish the system configuration
5. Obtain a model of the process, the actuator, and the sensor
6. Describe a controller and select key parameters to be adjusted
7. Optimize the parameters and analyze the performance

If the performance does not meet the specifications, then iterate the configuration

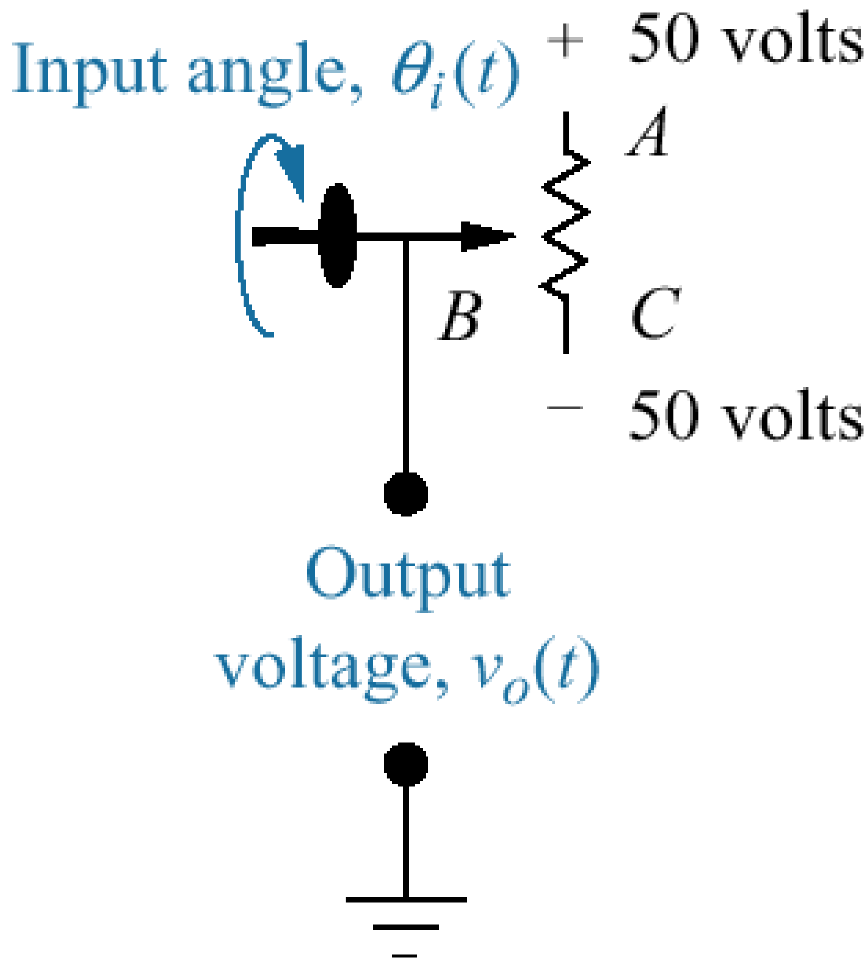
If the performance meets the specifications, then finalize the design.

Advantages of the Control Systems

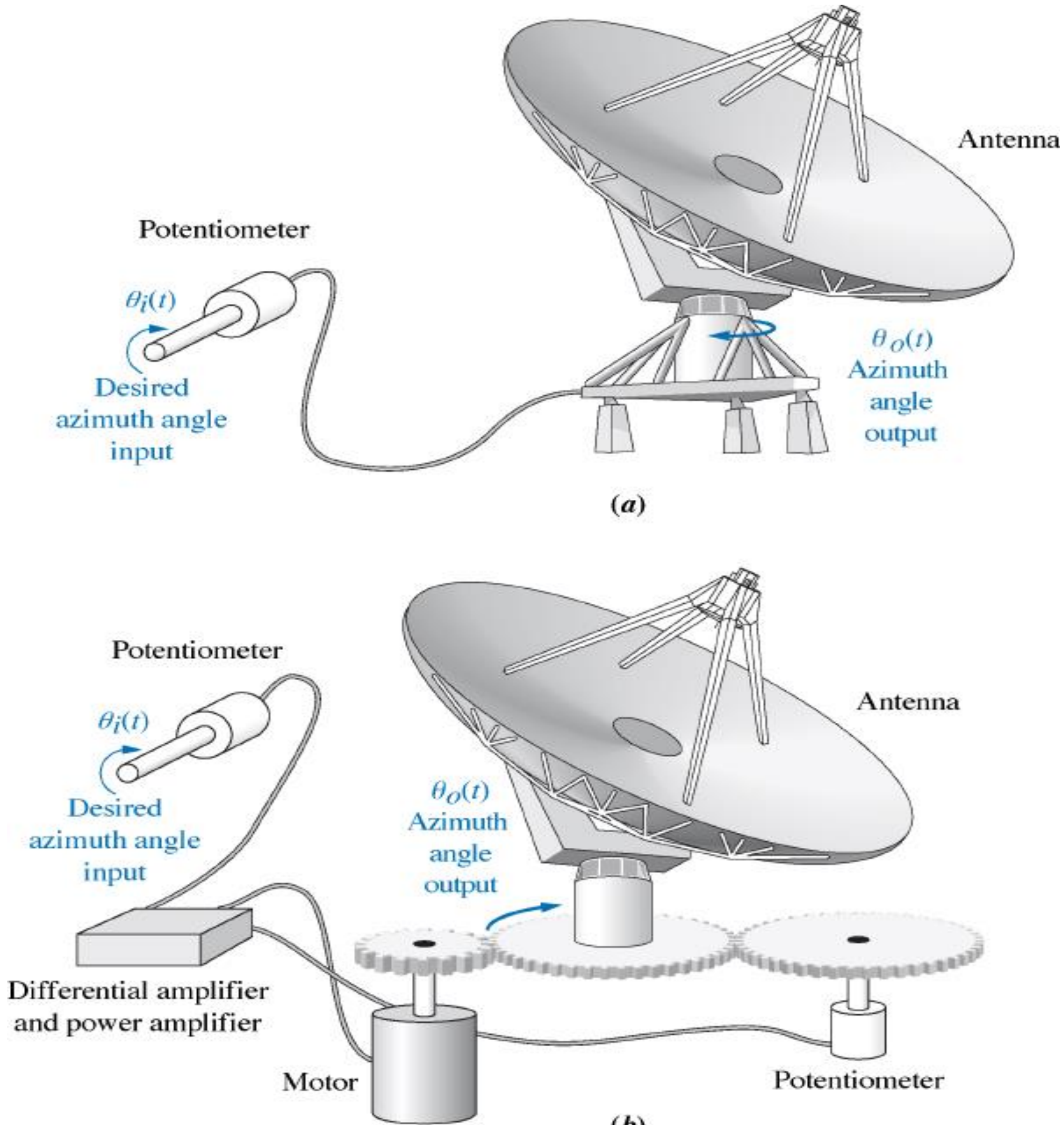
We build control systems for four primary reasons

1. Power amplification
2. Remote control
3. Convenience of input form
4. Compensation of the disturbances

Design Example



Antenna Azimuth Position Control



Illustrations

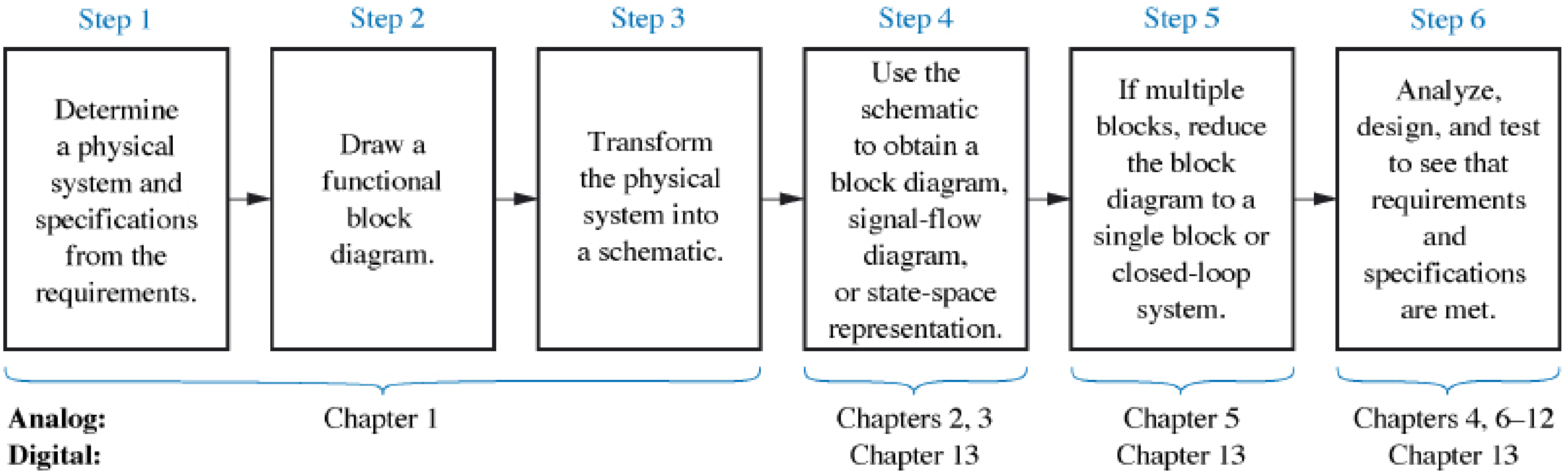
Design Stages for the Antenna

DESIGN PROCESS

The block diagram shows the design process step by step

Step 1: Determine the specifications such as transient response, steady- state error.
Step 2: Draw a functional block diagram and show interconnections of components
Step 3: Create a schematic and transform physical system to a schematic diagram
Step 4: Develop a mathematical model. Once schematic is drawn, designer uses physical laws, such as Kirchoff's laws for electrical network, Newton's for mech. sys.
Step 5: Reduce the block diagram to avoid unnecessary calculations

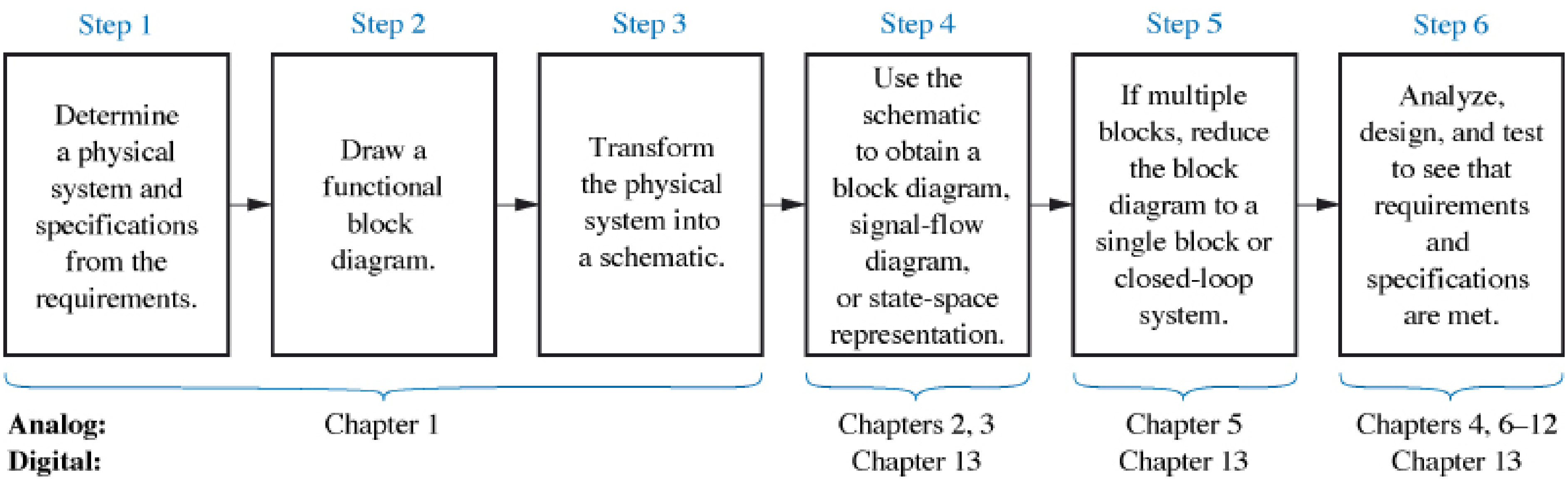
Step 6: Analyze and design the system.



DESIGN PROCESS…

The same block diagram presented below to see the design process step by step,

- After accomplishing the design steps, the Control Engineer analyzes the system to see if the response specifications and performance requirements can be met by simple adjustments of the system parameters.
- If specification cannot be met, the engineer then designs additional hardware in order to assure a desired performance.
- The engineer usually selects standard test inputs to analyze the system performance. These inputs are shown in Table 1.1



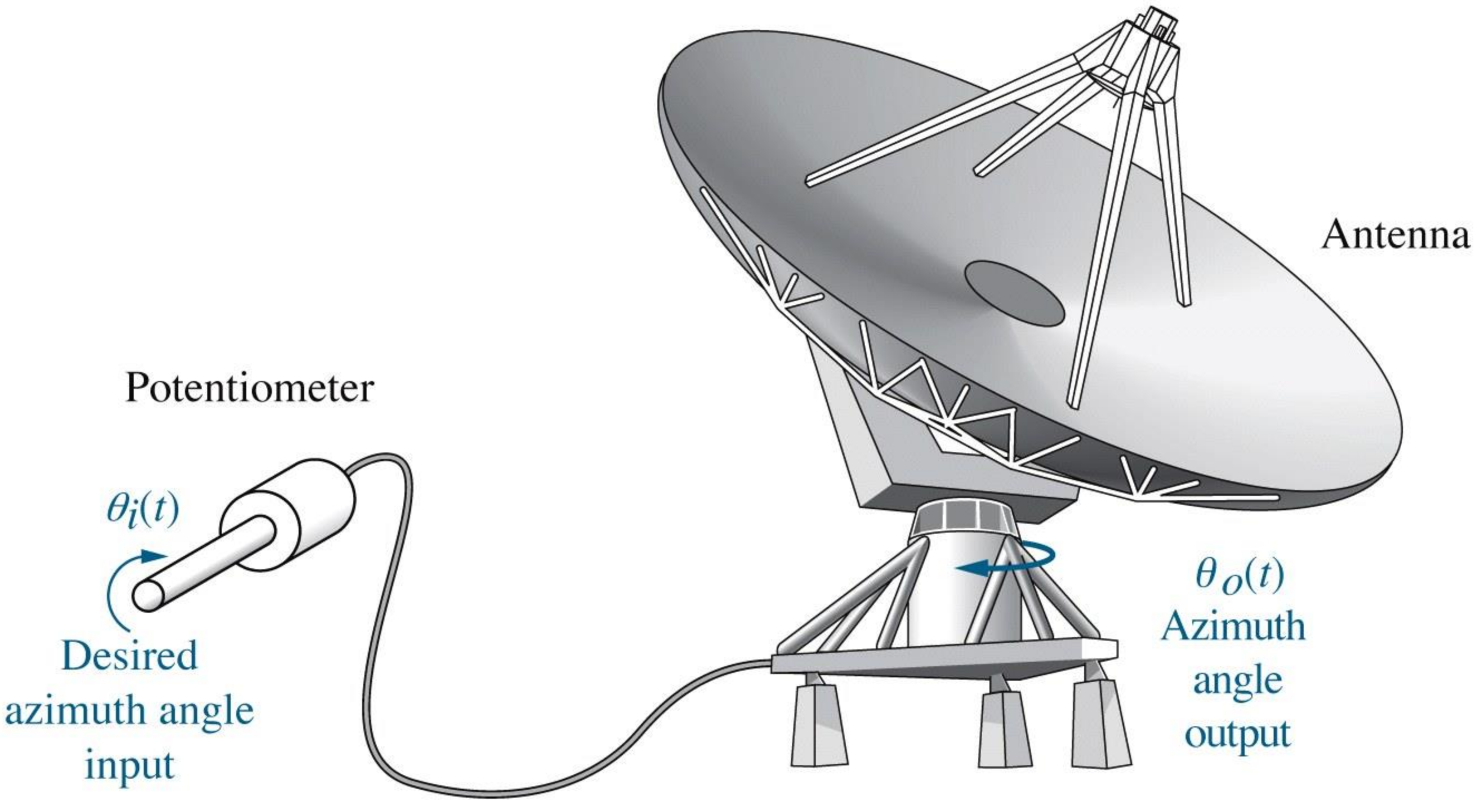
Step 1: Transform Requirements into a Physical System

Begin by transforming the requirements into a physical system.

For example, in the azimuth position control system, the requirements would be

- the desire to position the antenna from a remote location and
- describe such features as weight and physical dimensions.

Using the requirements, design specifications, such as desired transient response and steady-state accuracy, are determined.



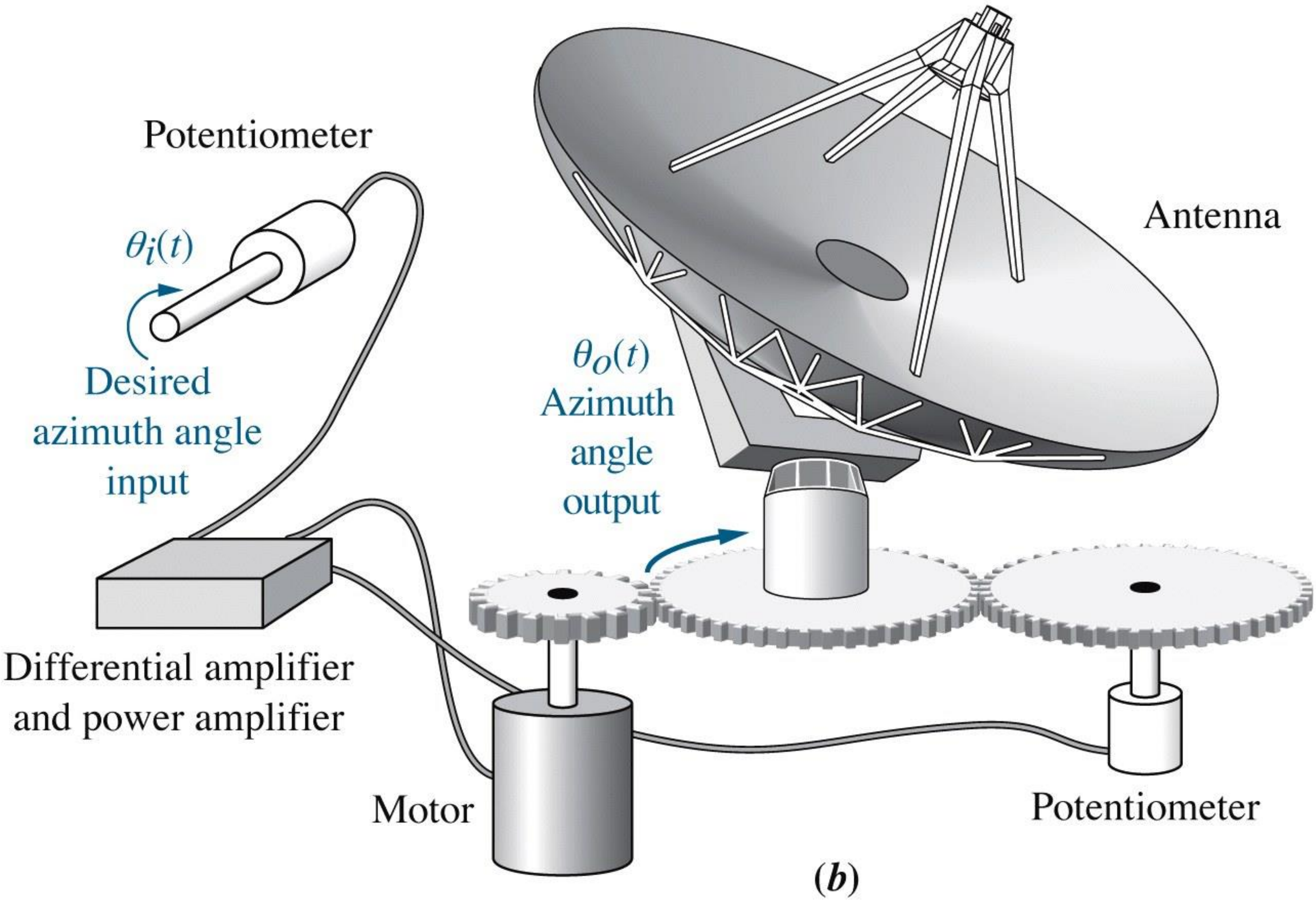

Potentiometer
$\theta_i(t)$
Desired
azimuth angle
input
$\theta_O(t)$
Azimuth
angle
output
Antenna
Differential amplifier
and power amplifier
Motor
Potentiometer
(b)

Figure 1.9b

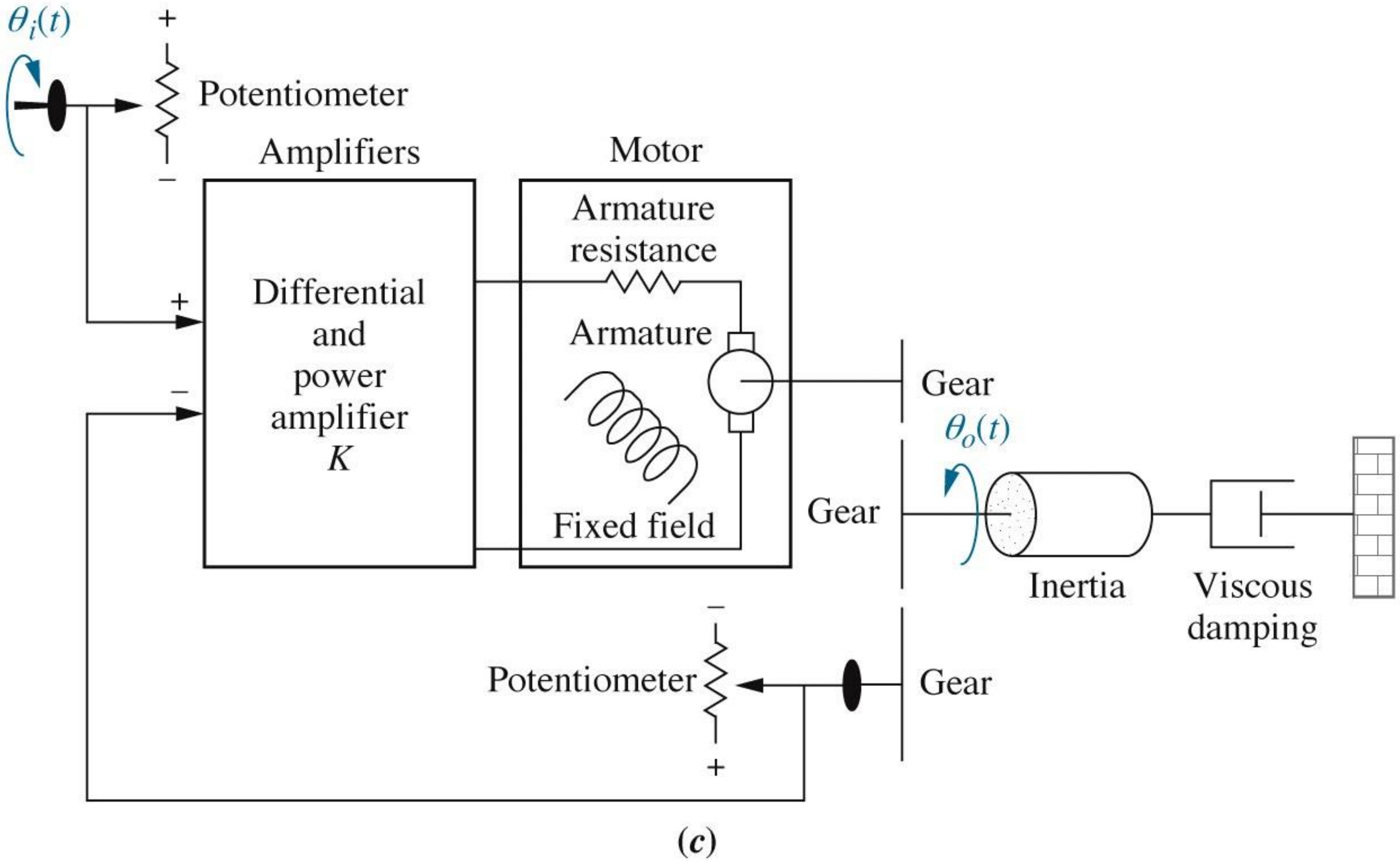
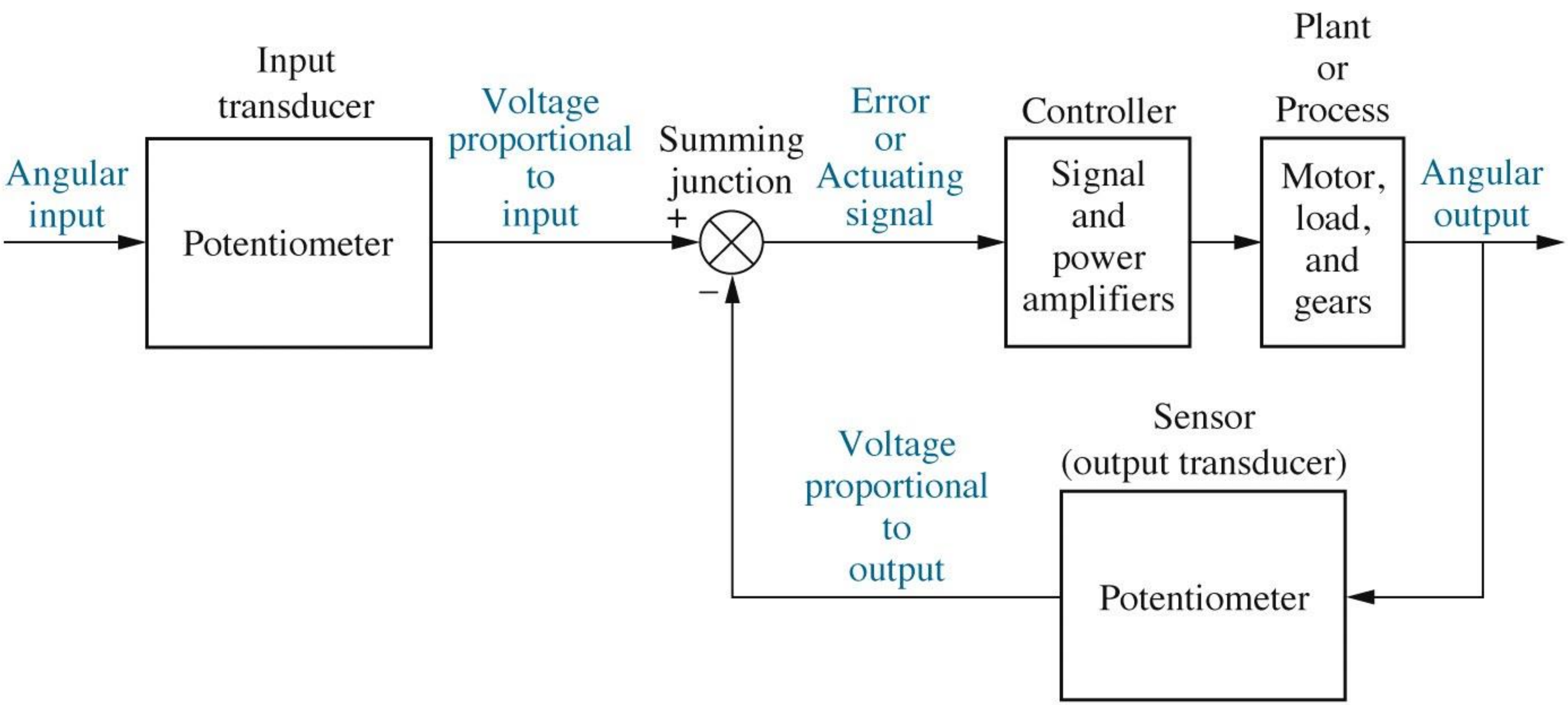

$\theta_i(t)$
+
Potentiometer
−
Amplifiers
Motor
+
−
Differential
and
power
amplifier
K
Armature
resistance
Armature
Fixed field
Gear
$\theta_o(t)$
Gear
Inertia
Viscous
damping
Gear
−
Potentiometer
+
(c)

Figure 1.9c

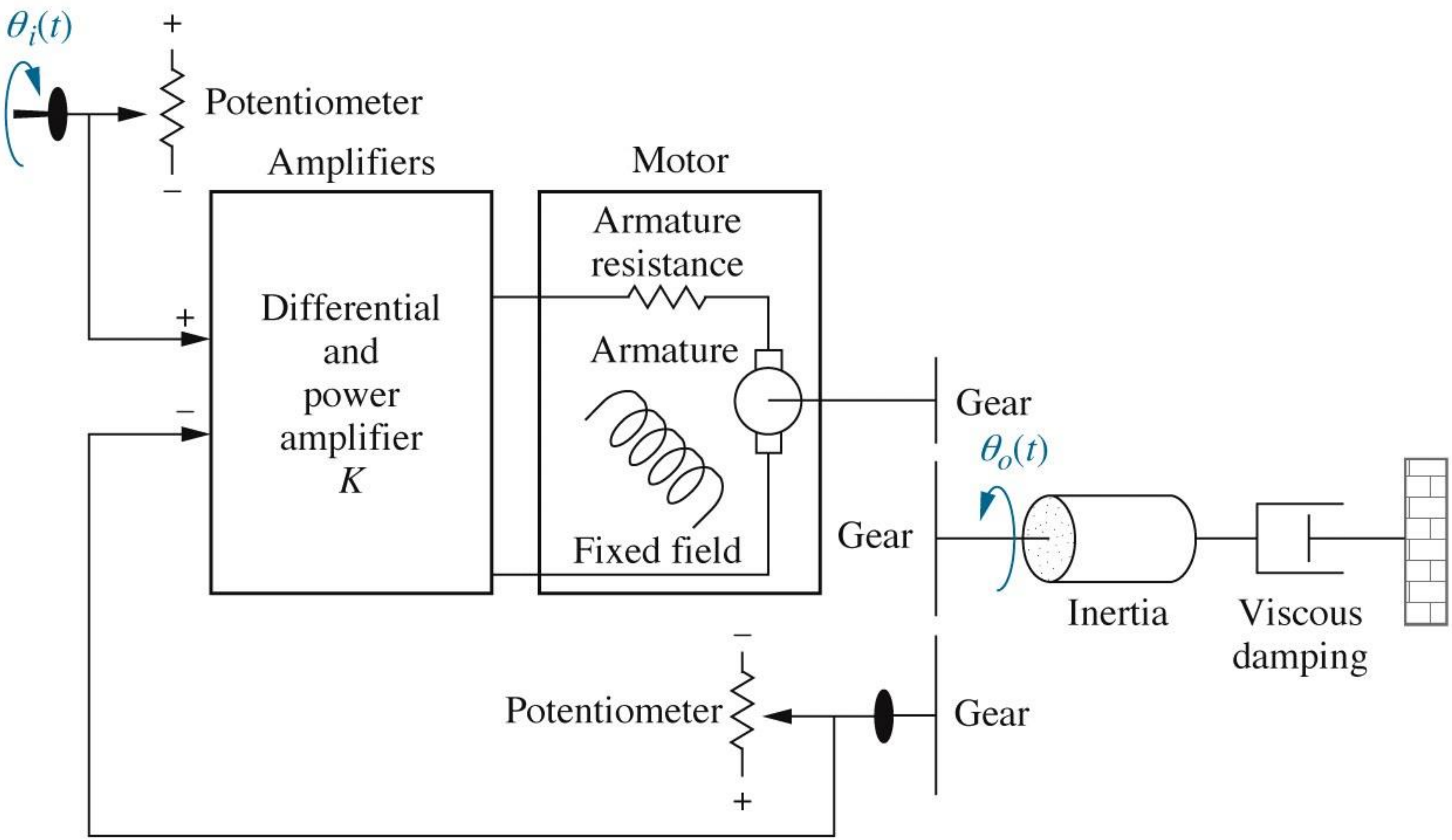
Step 2: Draw a Functional Block Diagram

The designer translates a qualitative description of the system into a functional block diagram that describes the component parts of the system (that is, function and/or hardware) and shows their interconnection.



Step-3: Draw Schematic

Antenna Azimuth System - Schematic

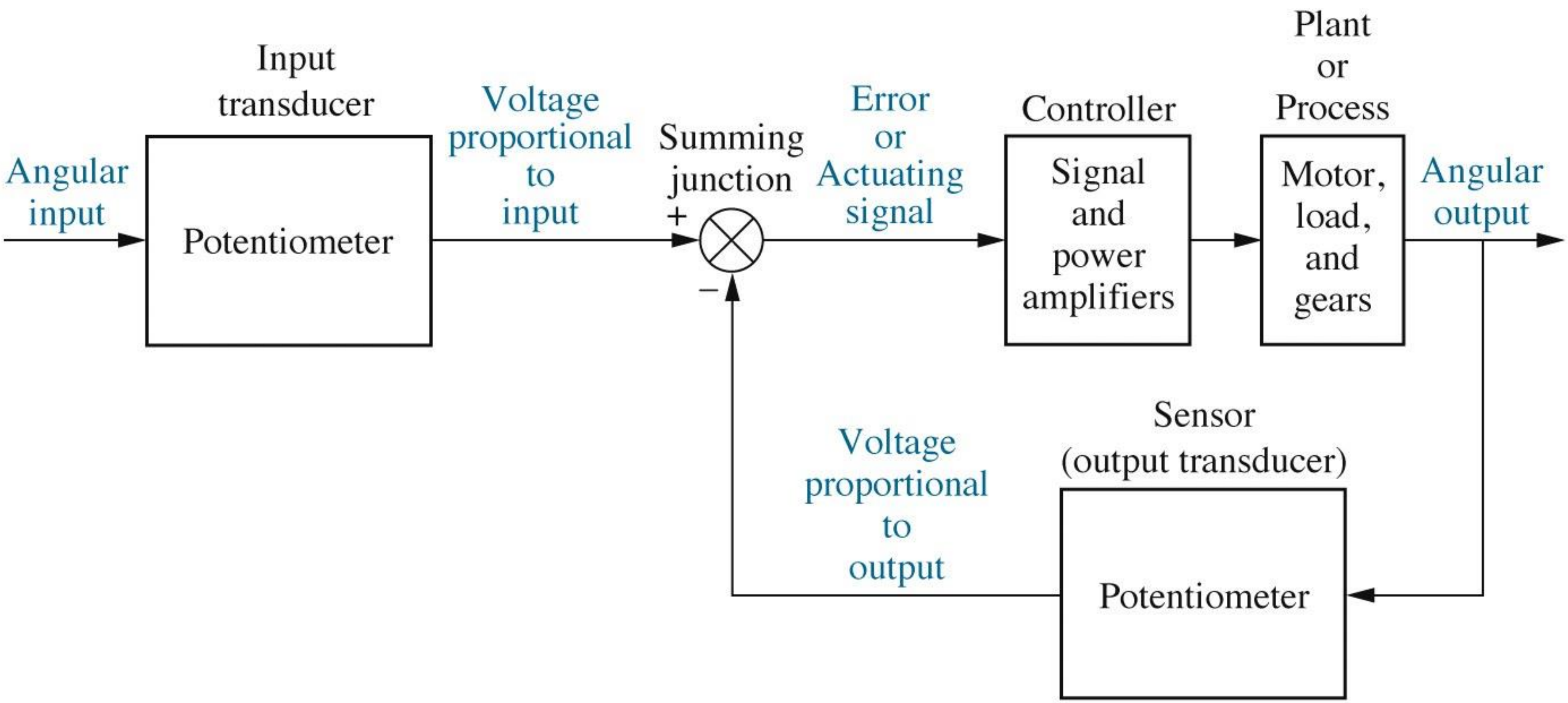


(c)

Figure 1.9c

Step-4: Draw Block Diagram

Antenna Azimuth System – Functional Block Diagram

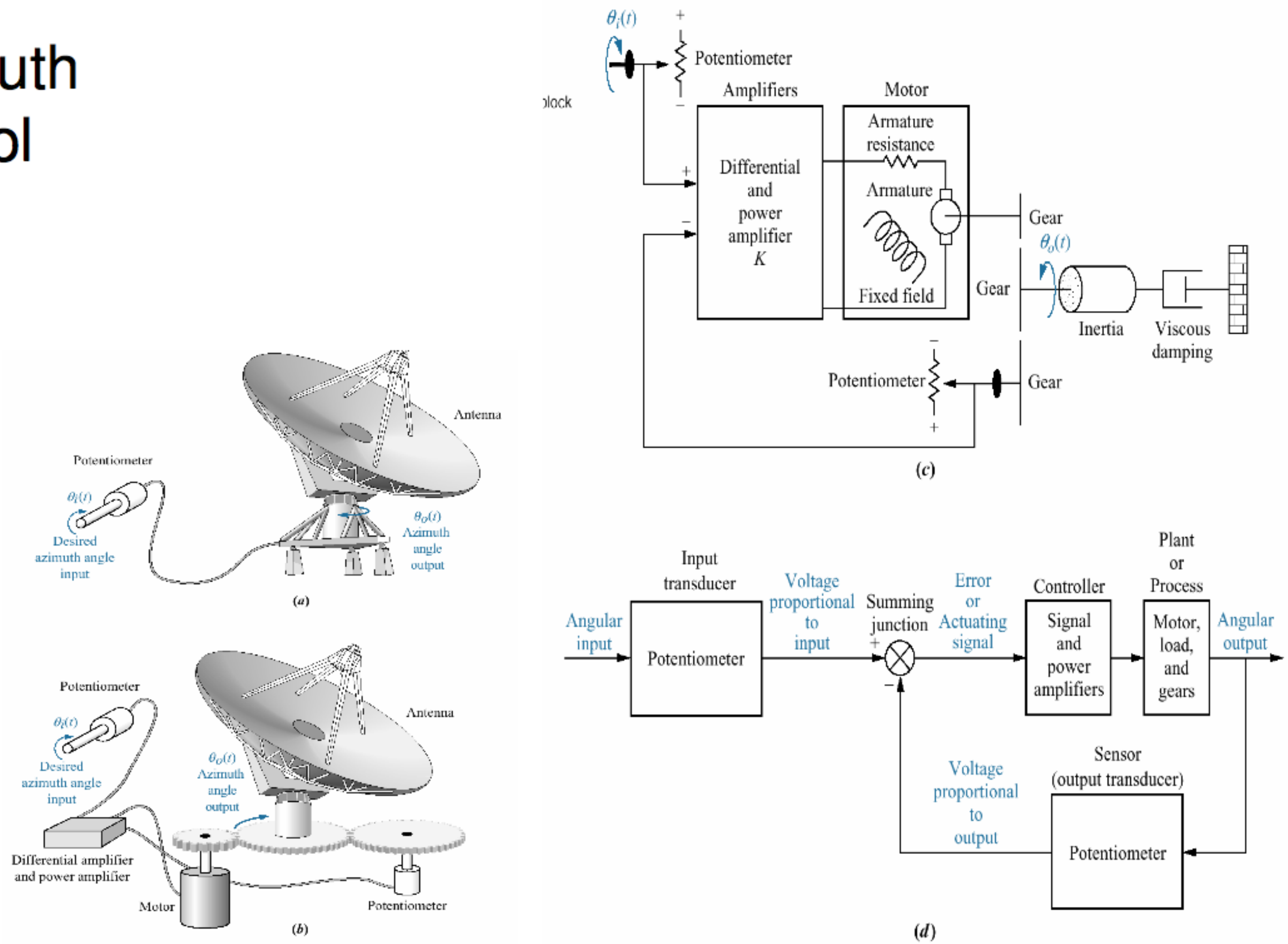


(*d*)

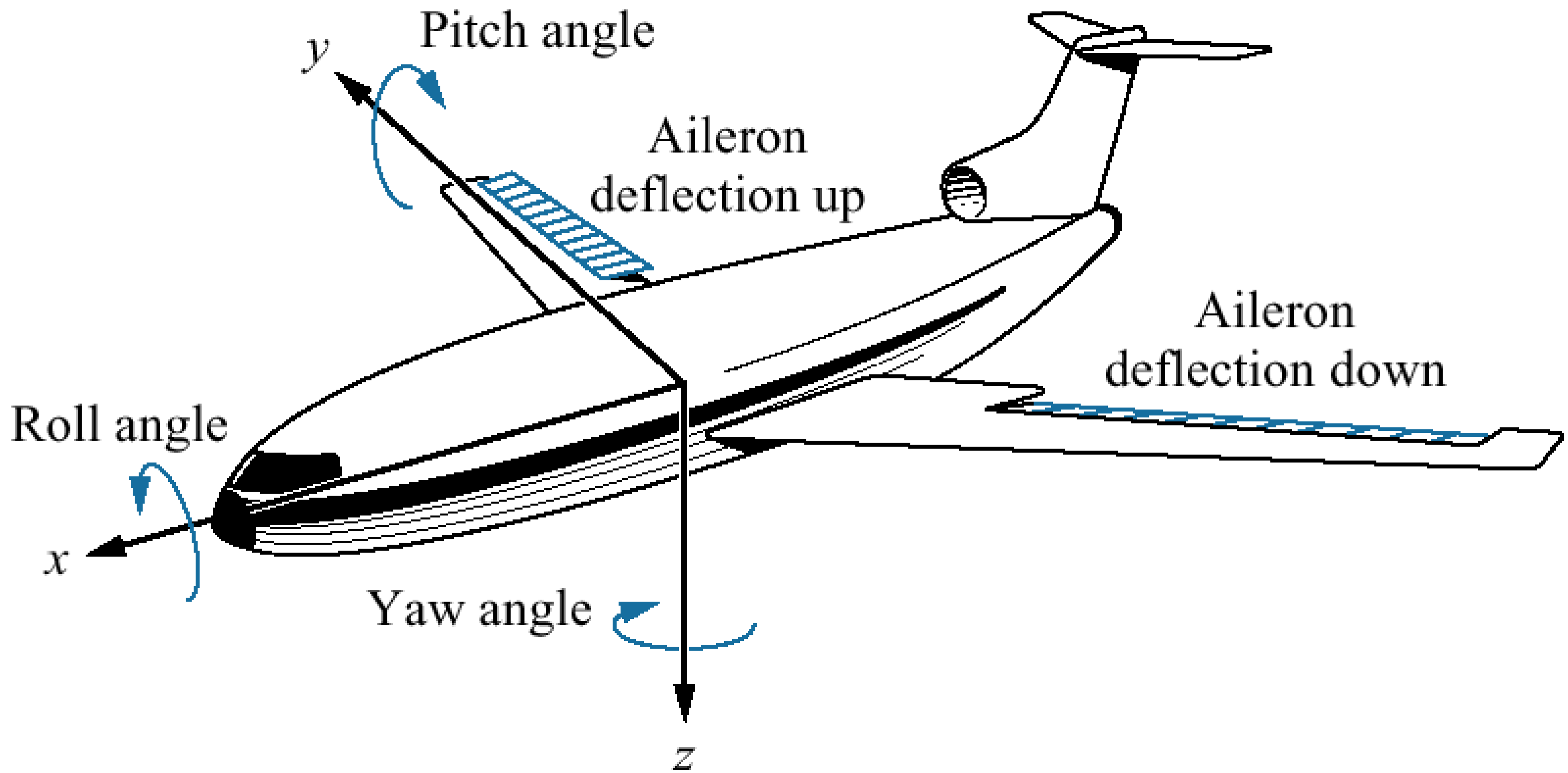
Figure 1.9d

Figure 1.9
Antenna azimuth position control system:

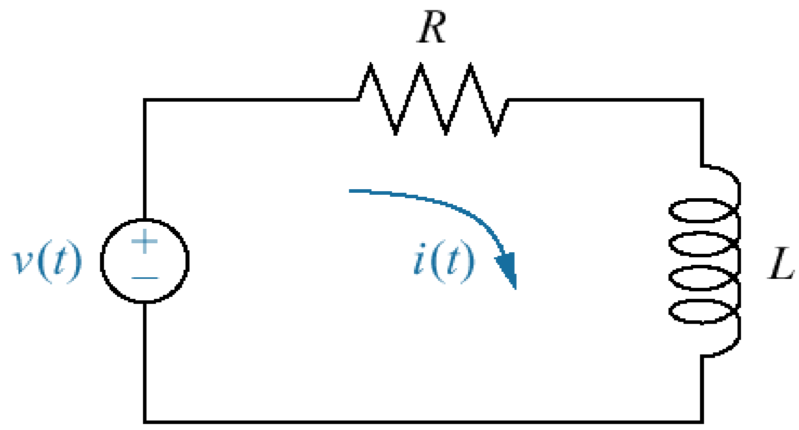
a. system concept;
b. detailed layout;
c. schematic;
d. functional block diagram

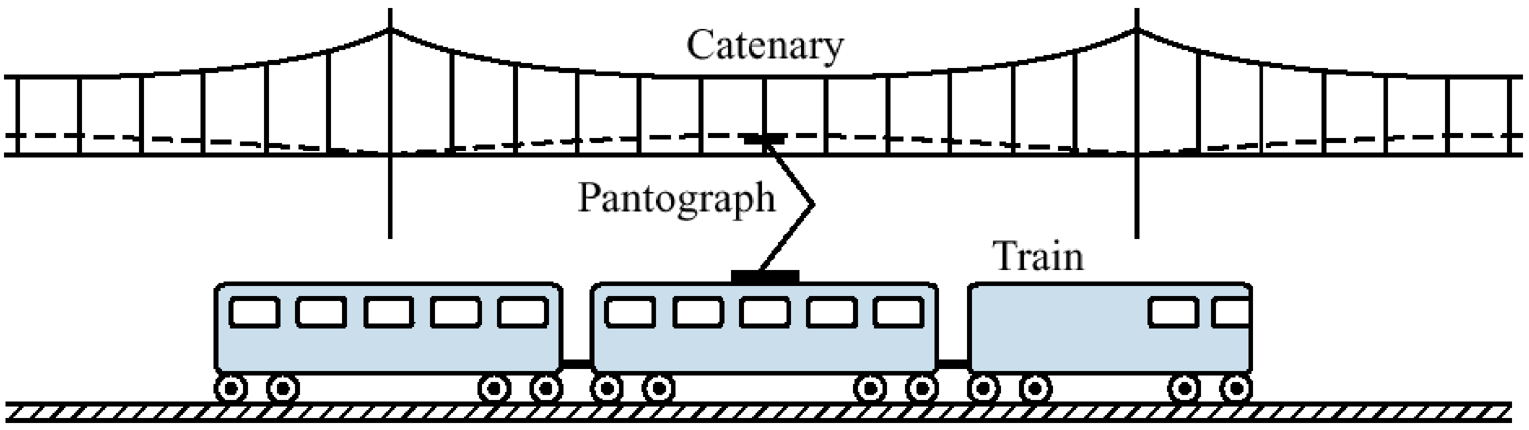


Design Example



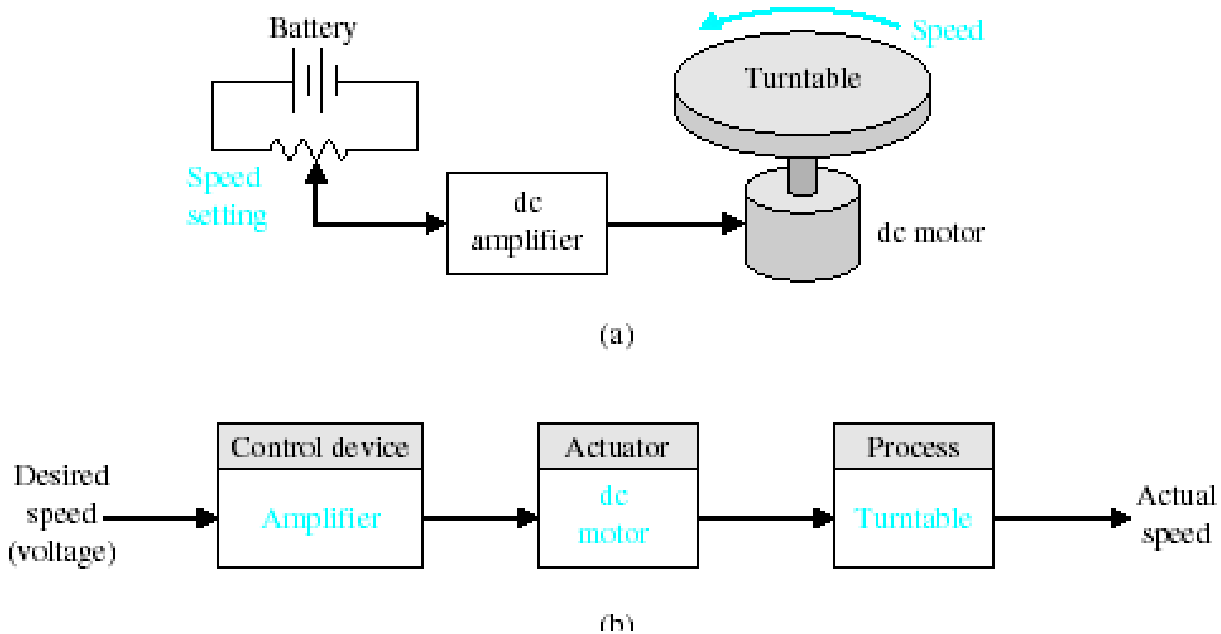
Design Example - Catenary





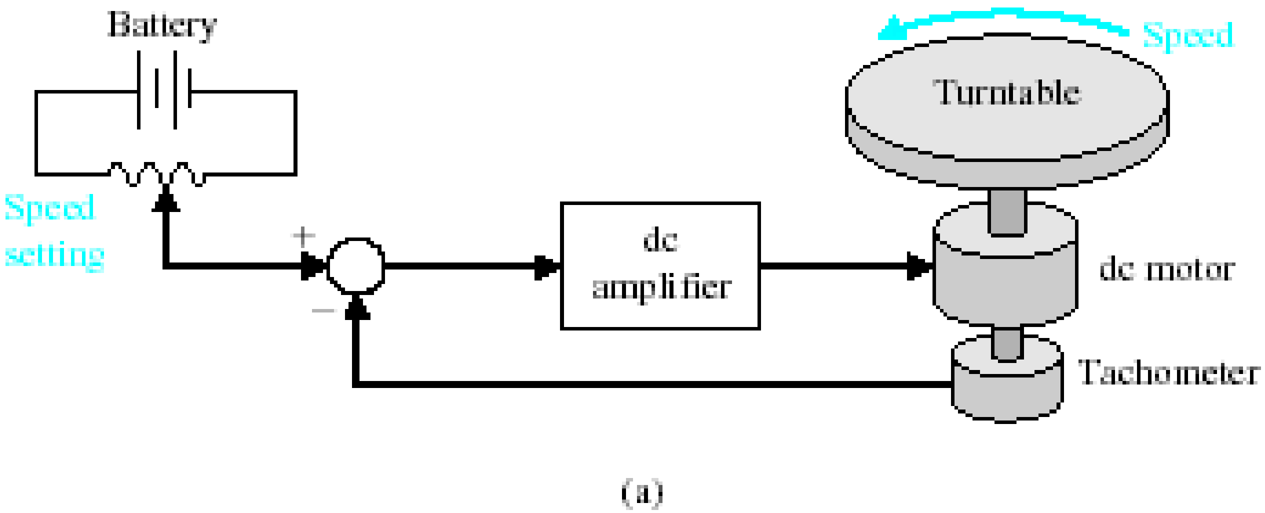
Design Example Turntable-1

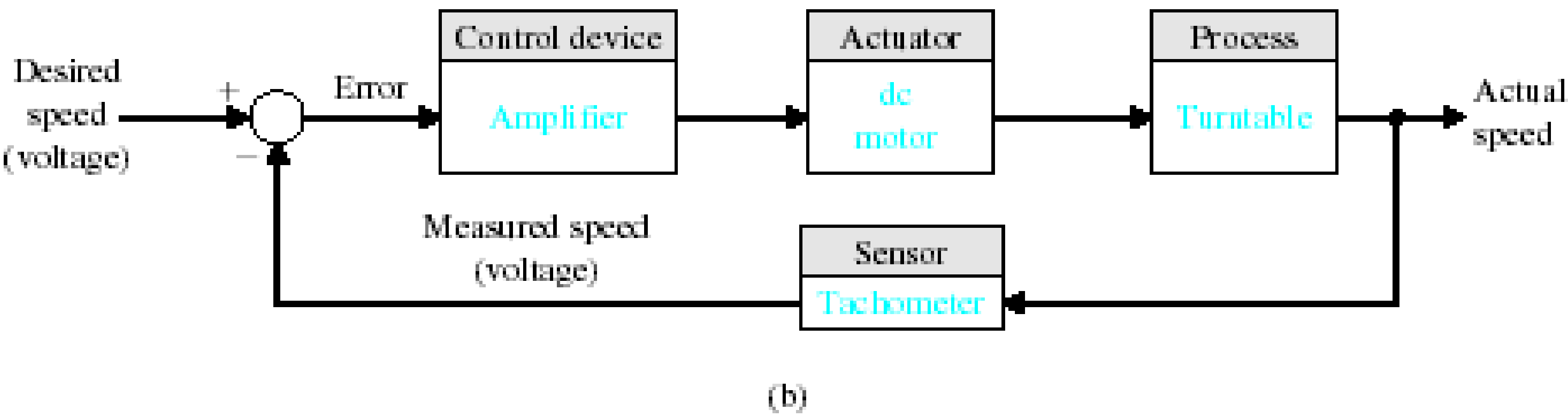
A turntable is the circular rotating platform of a phonograph (record player, gramophone, turntable, etc.), a device for playing sound recordings. The large ones are used as a positioner (for camera, etc).



(a) Open-loop (without feedback) control of the speed of a turntable.
(b) Block diagram model.

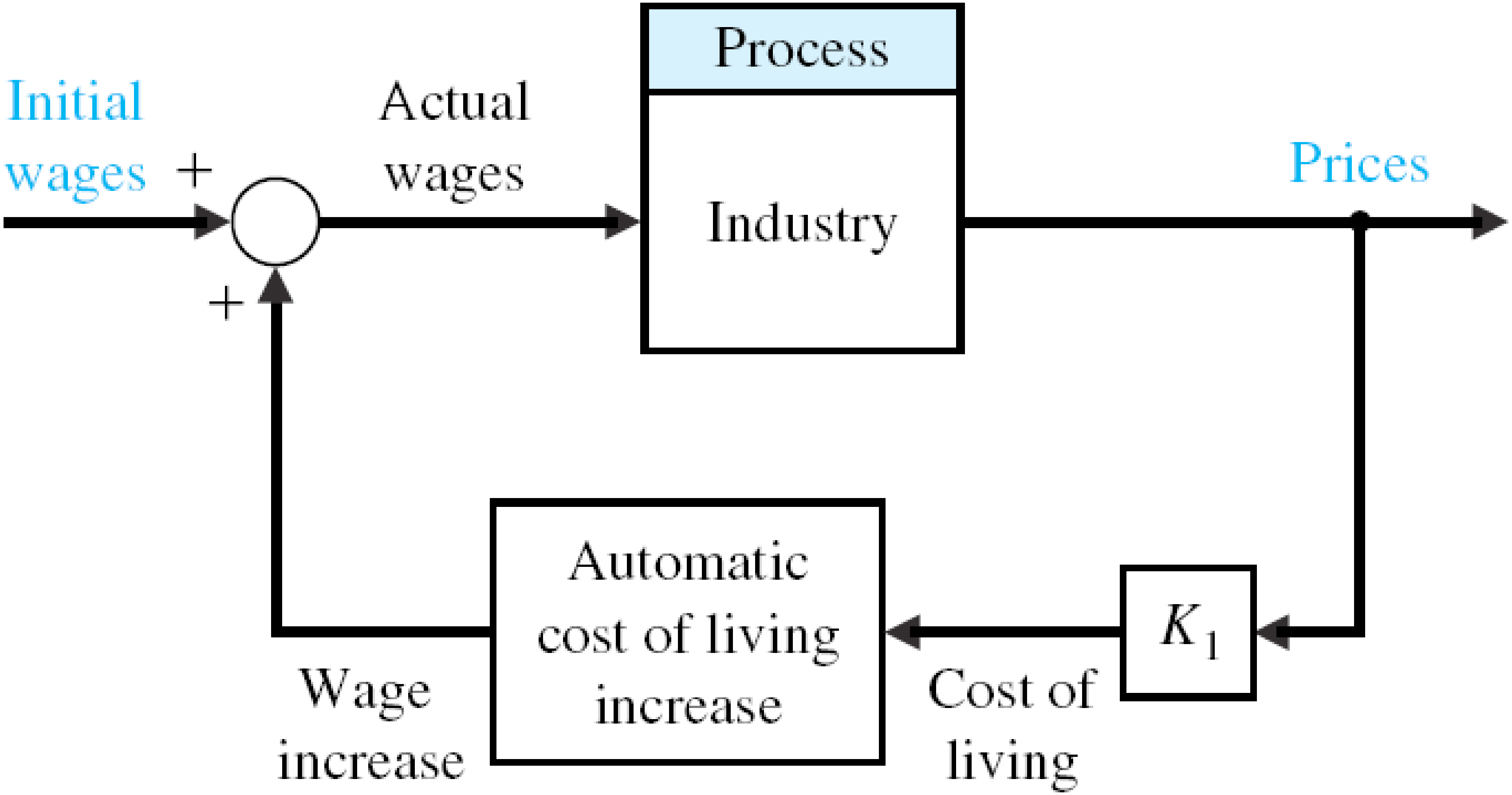
Design Example Turntable-2



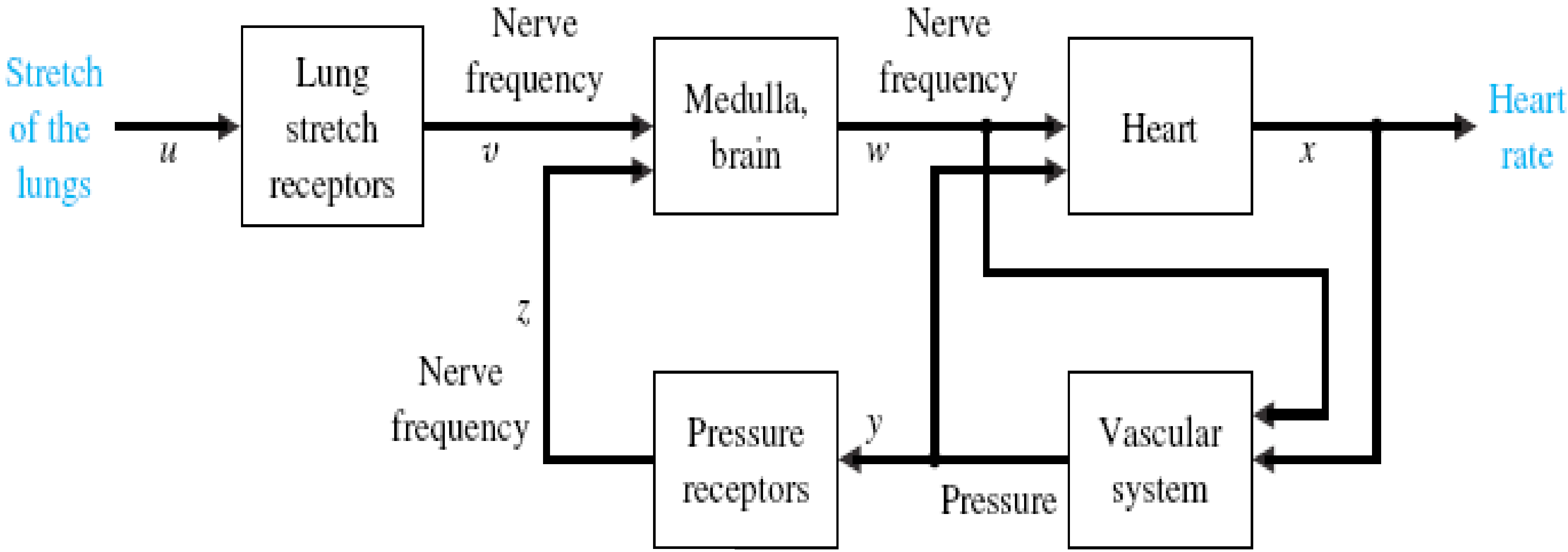


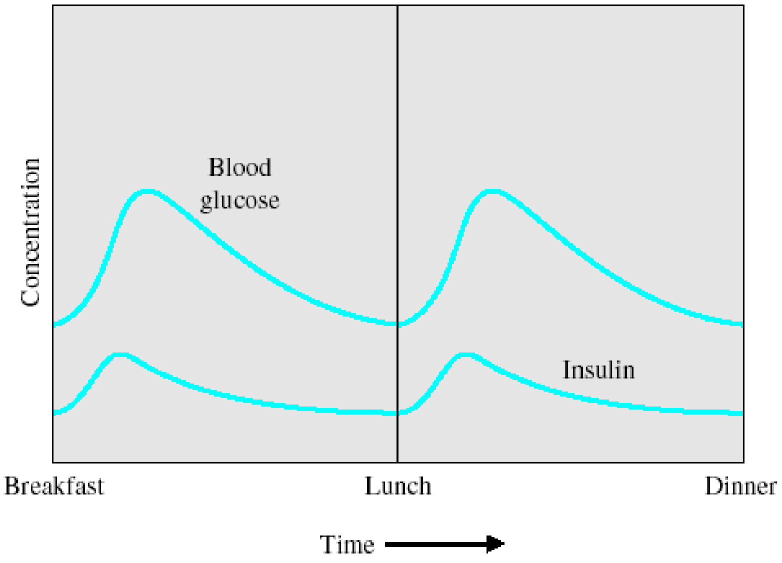
(a) Closed-loop control of the speed of a turntable.
(b) Block diagram model.

Example from Economics



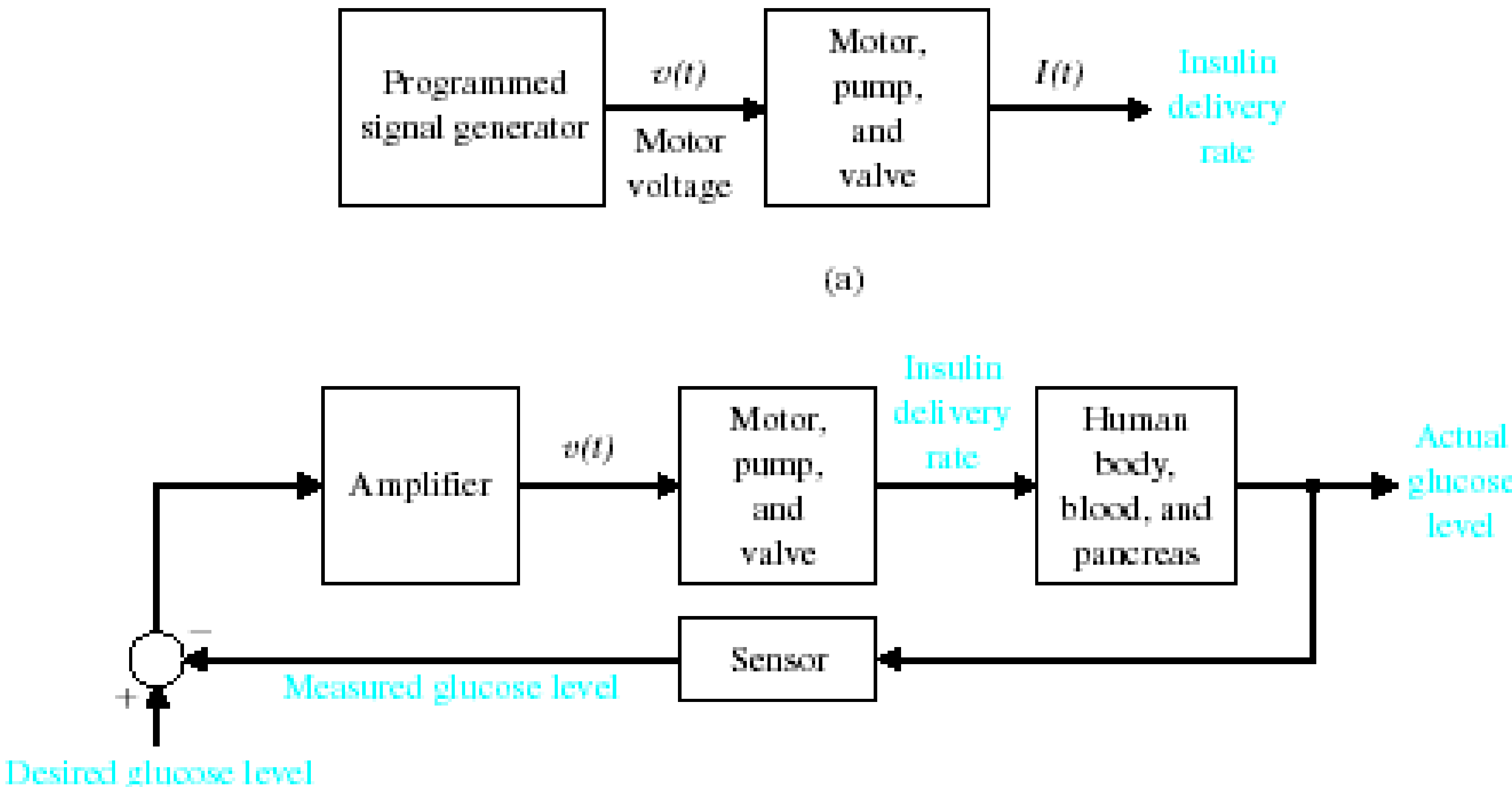
Example from a Biological System





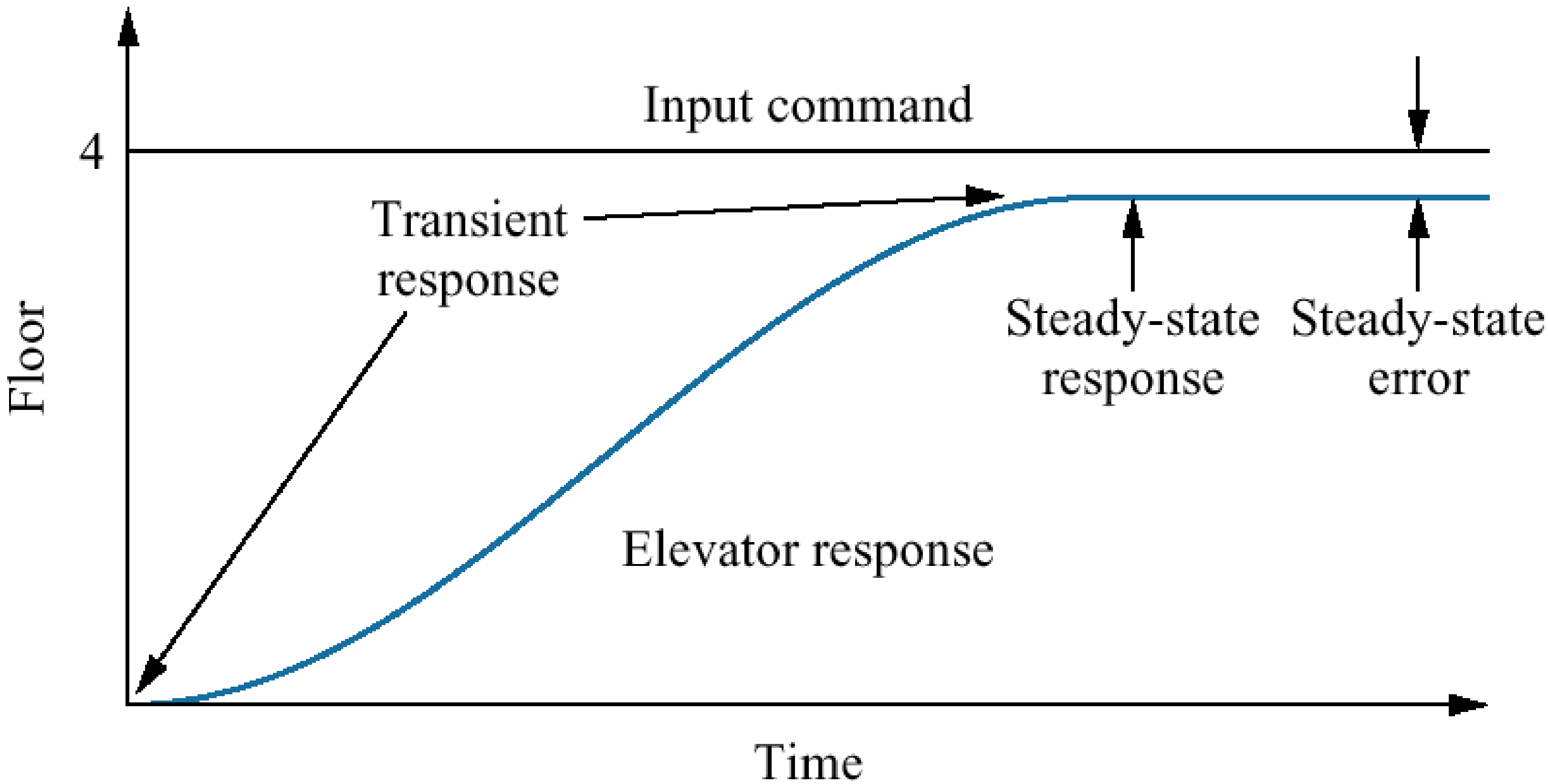
The blood glucose and insulin levels for a healthy person.

Design Example



(a) Open-loop (without feedback) control and
(b) closed-loop control of blood glucose.

Transient and steady state response



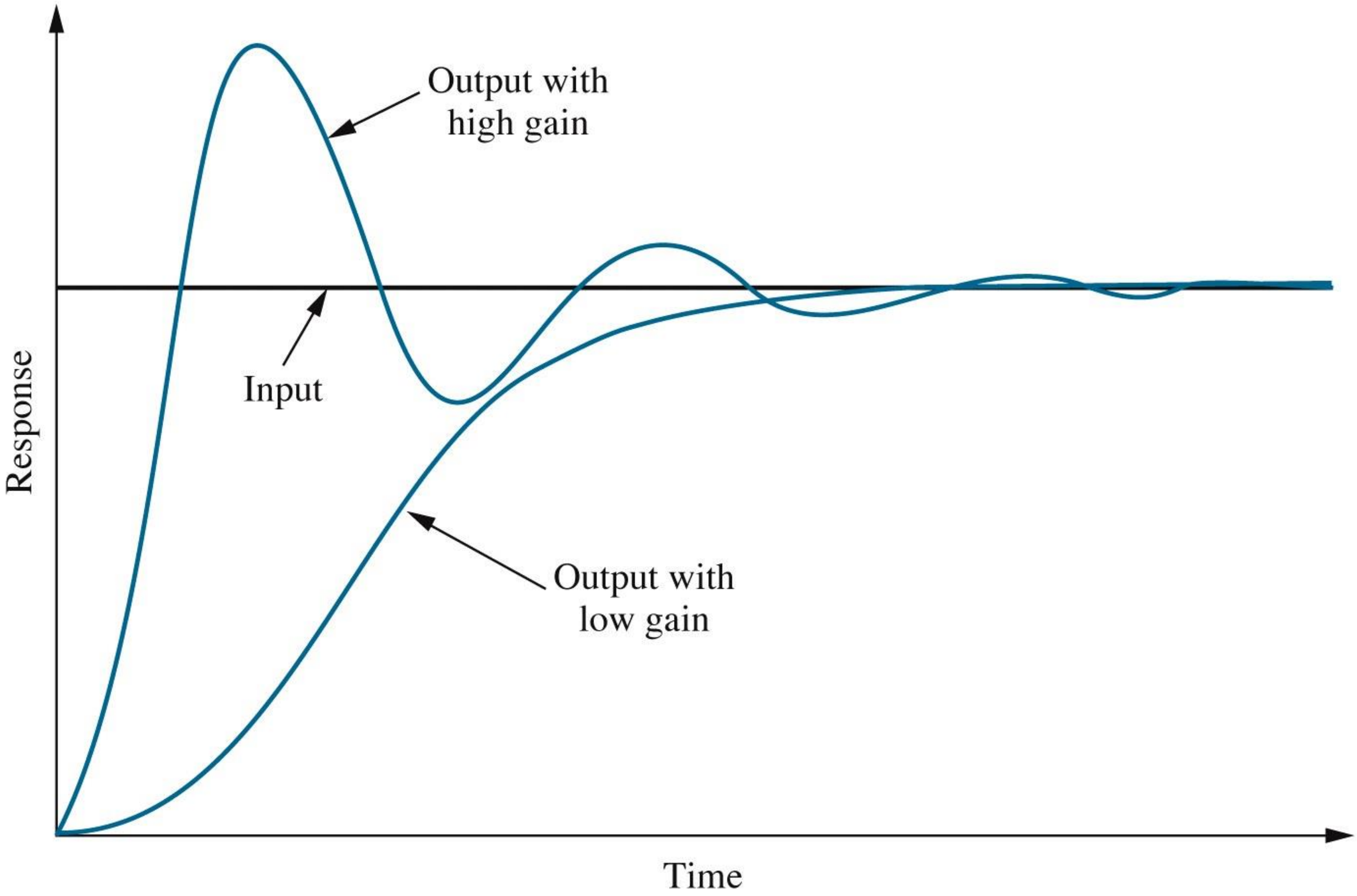

Output with
high gain
Input
Response
Output with
low gain
Time

Figure 1.10

Three terms needed to know

- Transient response
- Steady state response

  (transient response has decayed to zero remaining part resembles the input: output)
- Stability: most important thing in analysis and design objectives

Analysis and Design Objectives

- Transient Response must meet certain criteria.
  - ✓ Mainly: Speed and maximum overshoot.
- Steady-State Response must meet certain criteria.
  - ✓ Mainly: small or zero error
- Stability must be guaranteed.

✓ **Total Response = Natural Response + Forced Response**

- Natural response describes the way the system dissipates or gain energy. It is dependent only on the system not the input
- Forced response depends on the input.
- Natural response must go to zero leaving only the forced response or oscillate