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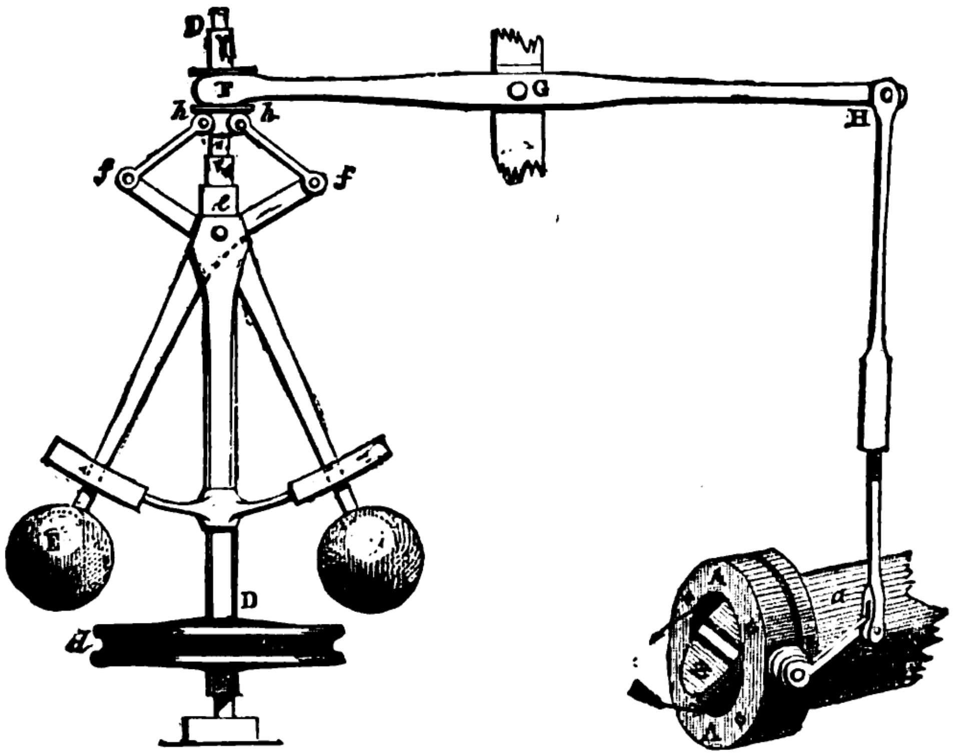

Control System Design

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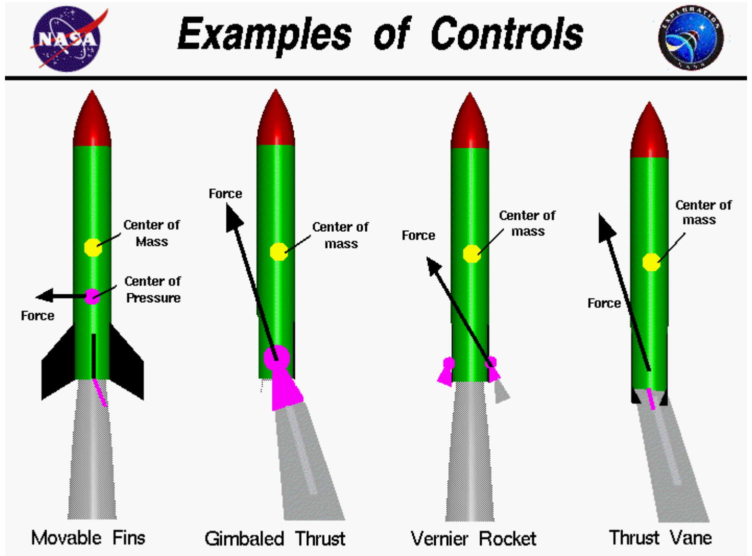
Control systems are an integral part of modern society.

Numerous applications are all around us:

- The rockets fire, and the space shuttle lifts off to earth orbit;
- In splashing cooling water, a metallic part is automatically machined CNC;
- A self-guided vehicle delivering material to workstations



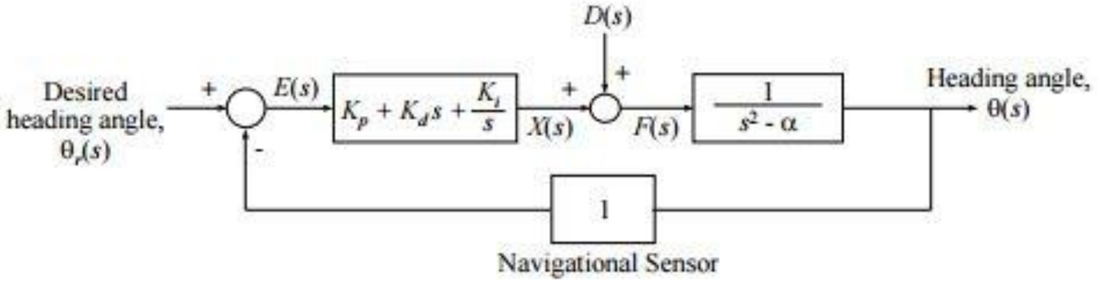
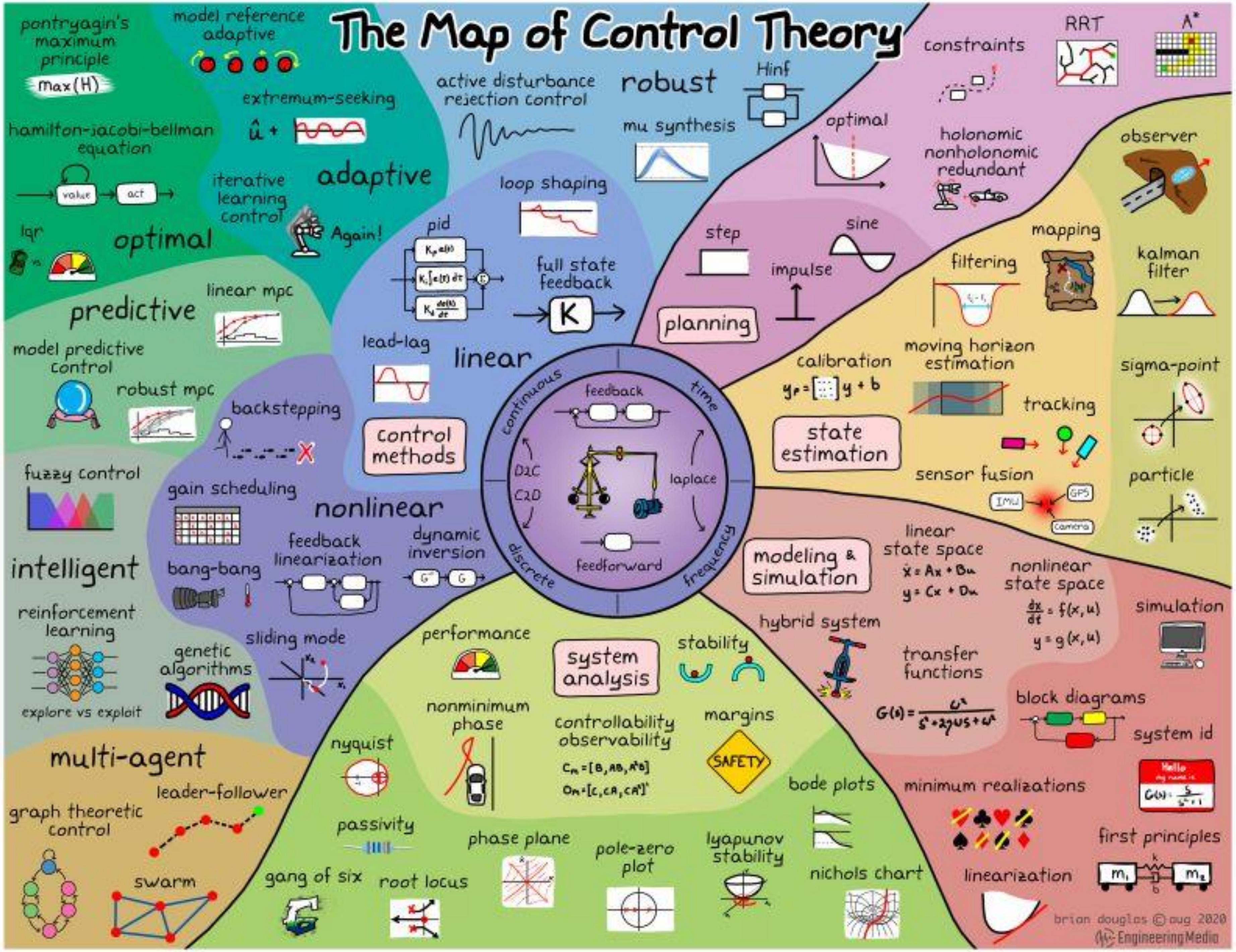


Figure 2: Automatic booster rocket heading control system



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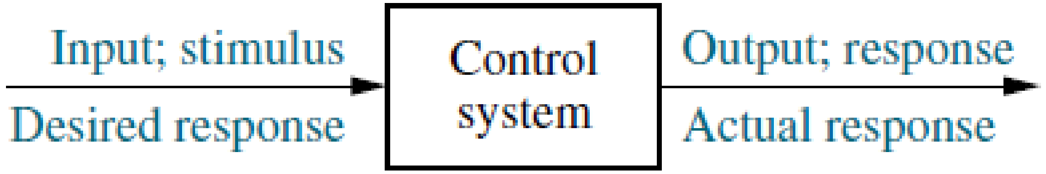
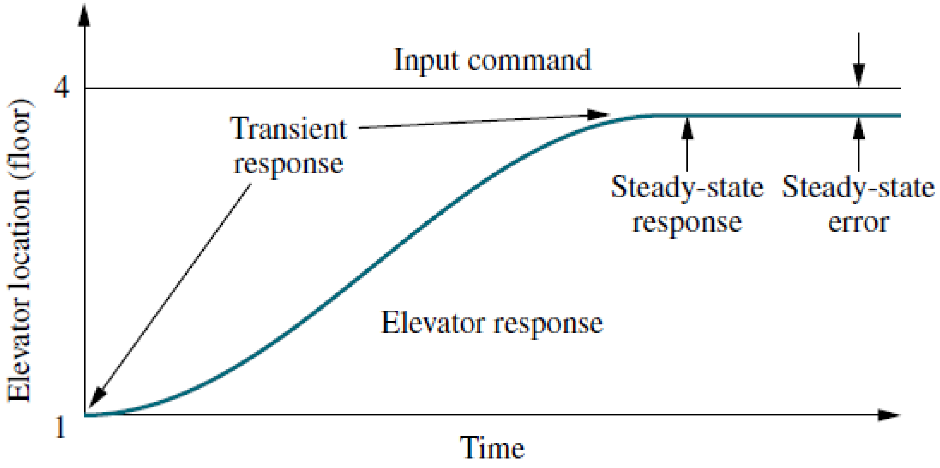
Control System Definition

A control system consists of subsystems and processes (or plants) assembled for the purpose of obtaining a desired output with desired performance, given a specified input.

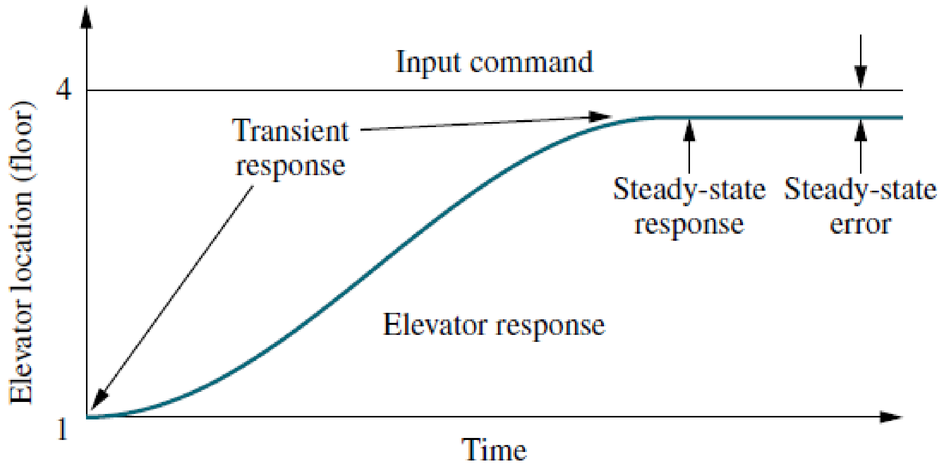


For example, consider an elevator. When the fourth-floor button is pressed on the first floor, the elevator rises to the fourth floor with a speed and floor-leveling accuracy designed for passenger comfort. The push of the fourth-floor button is an input that represents our desired output, shown as a step function



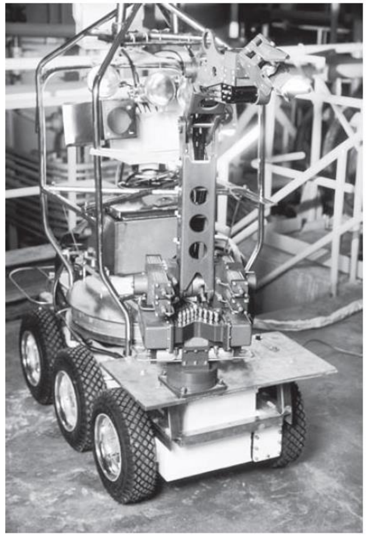
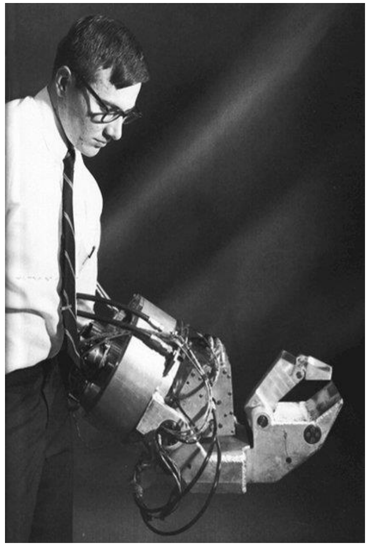
Advantages of Control Systems

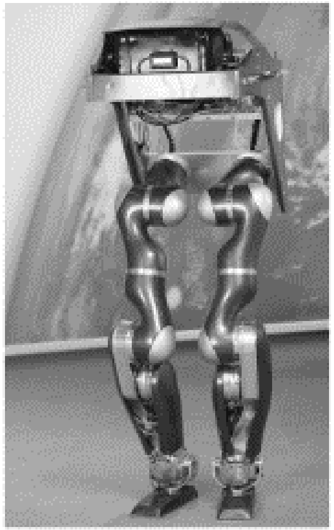
Two major measures of performance are apparent:
(1) the transient response
(2) the steady-state error.



We build control systems for four primary reasons:

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

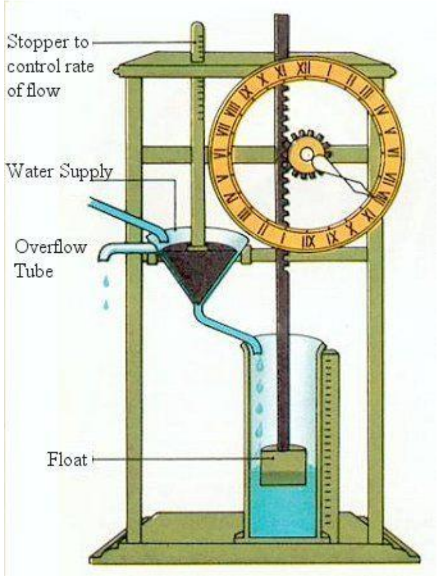



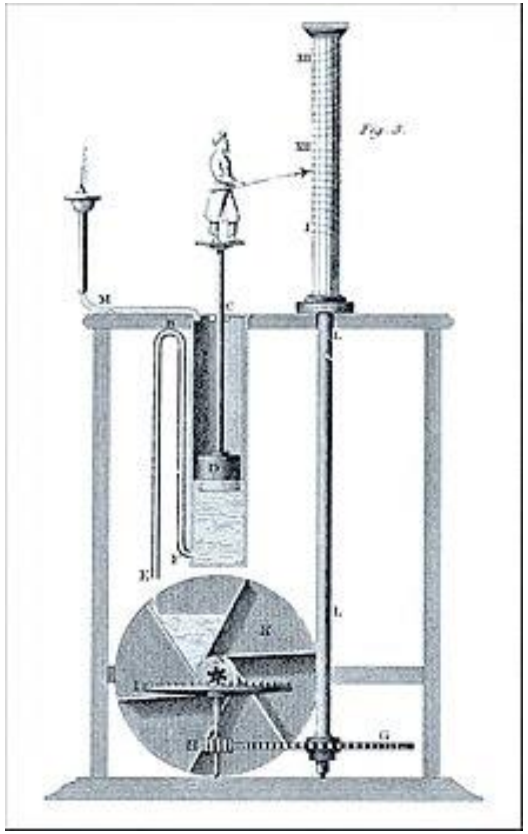


A History of Control Systems

Feedback control systems are older than humanity. Numerous biological control systems were built into the earliest inhabitants of our planet.

TheGreeks began engineering feedback systems around 300 B.C. A water clock invented by Ktesibios operated by having water trickle into a measuring container at a constant rate





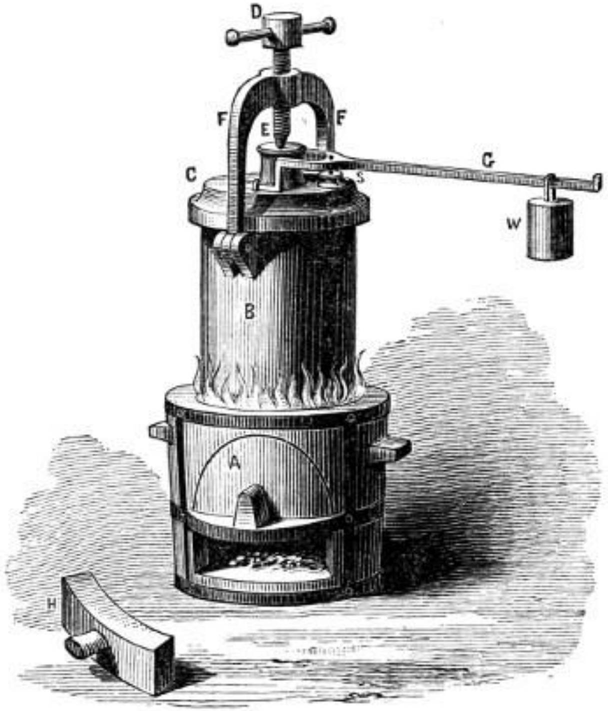
https://www.ancientworldreview.com/2016/09/greeks-invented-the-first-mechanical-clock.html

A History of Control Systems

Steam Pressure and Temperature Controls

Regulation of steam pressure began around 1681 with Denis Papin’s invention of the safety valve. The concept was further elaborated on by weighting the valve top. If the upward pressure from the boiler exceeded the weight, steam was released, and the pressure decreased.

If it did not exceed the weight, the valve did not open, and the pressure inside the boiler increased.



A History of Control Systems

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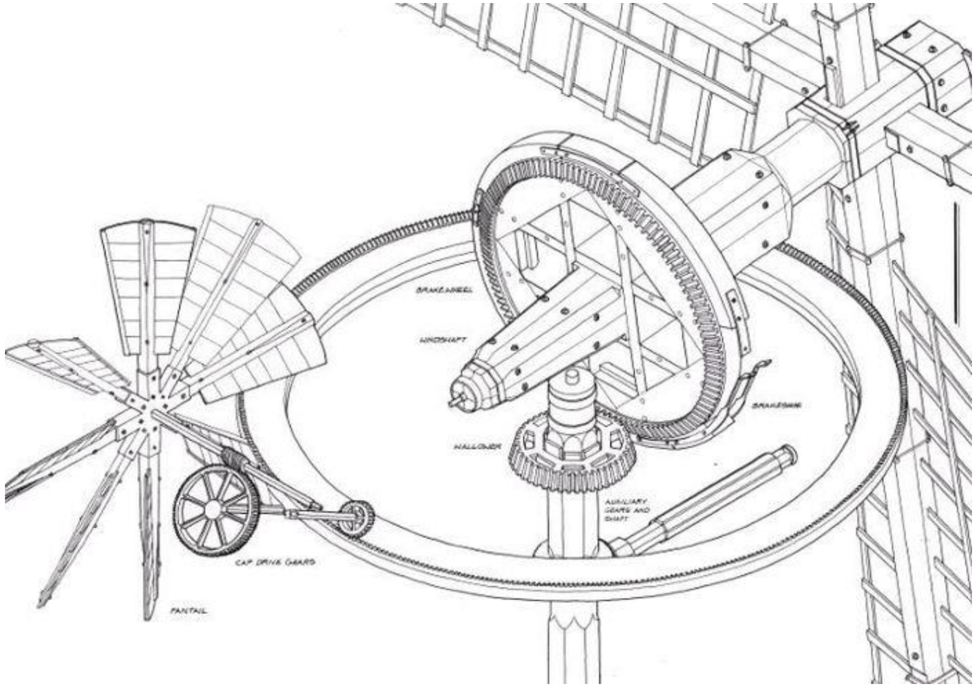
Speed Control

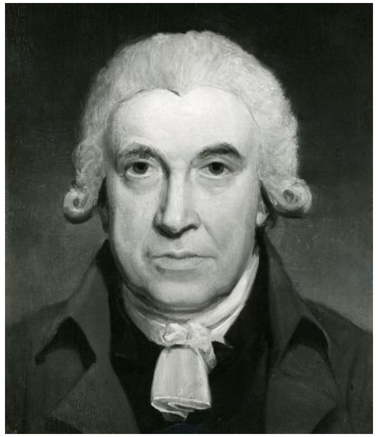
In 1745, speed control was applied to a windmill by Edmund Lee. Increasing winds pitched the blades farther back, so that less area was available.
As the wind decreased, more blade area was available.

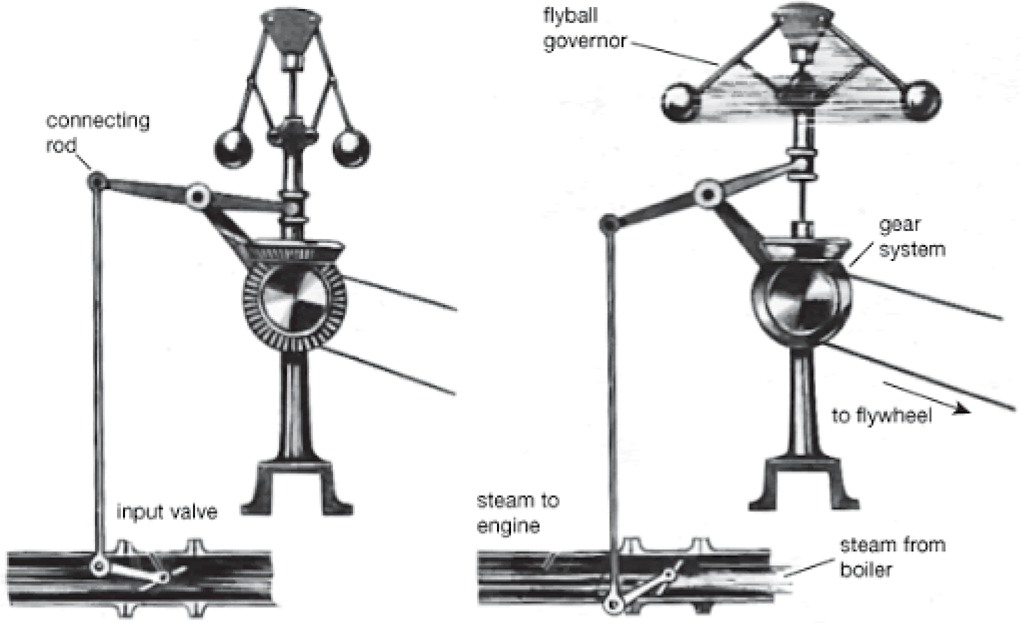


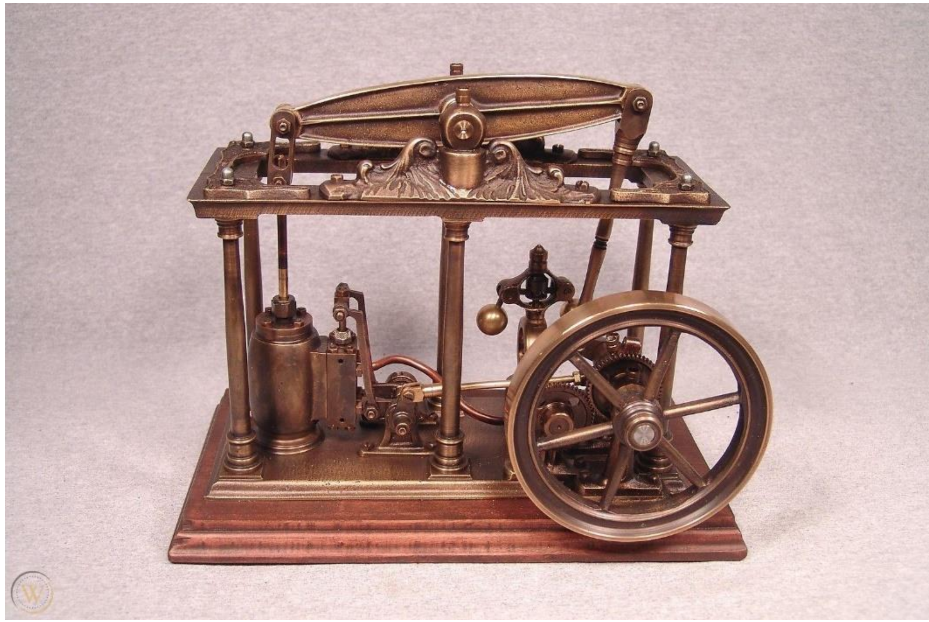
A History of Control Systems

Speed Control

Also in the eighteenth century, **James Watt** invented the fly ball speed governor to control the speed of steam engines. In this device, two spinning fly balls rise as rotational speed increases. A steam valve connected to the fly ball mechanism closes with the ascending fly balls and opens with the descending fly balls, thus regulating the speed.

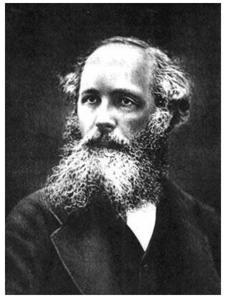




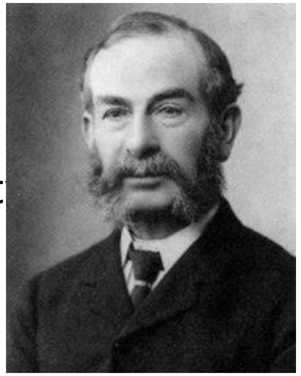


A History of Control Systems

Stability concepts



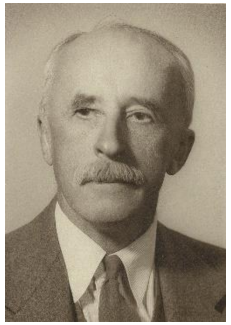
In 1868, **James Clerk Maxwell** published the stability criterion for a third-order system based on the coefficients of the differential equation



In 1874, **Edward John Routh**, using a suggestion from William Kingdon Clifford that was ignored earlier by Maxwell, was able to extend the stabilit criterion to fifth-order systems.

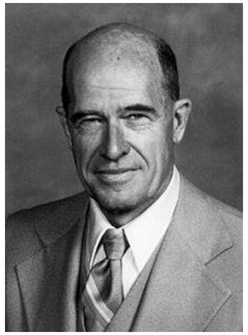
A student of **P. L. Chebyshev** at the University of St. Petersburg in Russia, **Lyapunov** extended the work of Routh to nonlinear systems in his 1892 doctoral thesis, entitled *The General Problem of Stability of Motion.*

A History of Control Systems



However, much of the general theory used today to improve the performance of automatic control systems is attributed to **Nicholas Minorsky**, a Russian born in 1885.
It was his theoretical development applied to the automatic steering of ships that led to what we call today **proportional-plus-integral-plus-derivative (PID)**, or three-mode, controllers.


In the late 1920s and early 1930s, **H.W. Bode and H. Nyquist** at **Bell** Telephone Laboratories developed the analysis of feedback amplifiers. These contributions evolved into sinusoidal frequency analysis and design techniques currently used for feedback control system.



In 1948, **Walter R. Evans**, working in the aircraft industry, developed a graphical technique to plot the roots of a characteristic equation of a feedback system whose parameters changed over a particular range of values. This technique, now known as the **root locus**, takes its place with the work of **Bode and Nyquist** in forming the <u>*foundation of linear control systems analysis and design theory*</u>

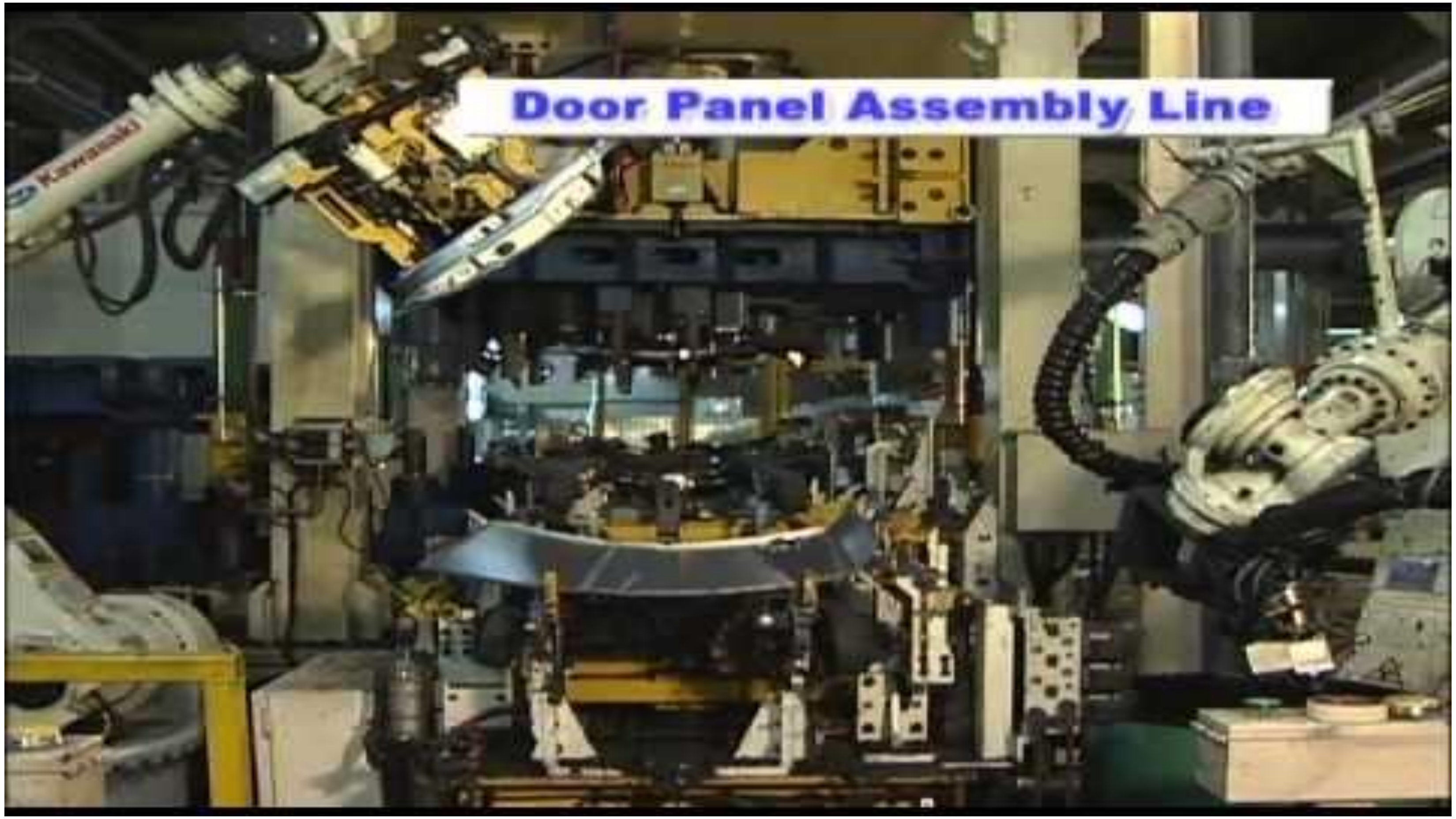
Contemporary Applications

Today, control systems find widespread application in the guidance, navigation, and control of missiles and spacecraft, as well as planes and ships at sea

Modern ships use a combination of electrical, mechanical, and hydraulic components to develop rudder commands in response to desired heading commands.

We find control systems throughout the process control industry, regulating liquid levels in tanks, chemical concentrations in vats, as well as the thickness of fabricated material (checked by Xrays)

Example of production line

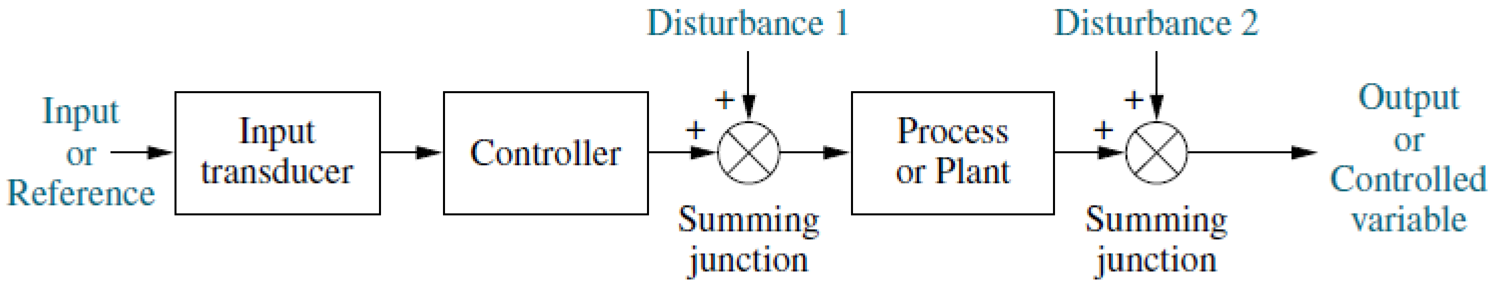


https://www.youtube.com/watch?v=LVesntEA2s0

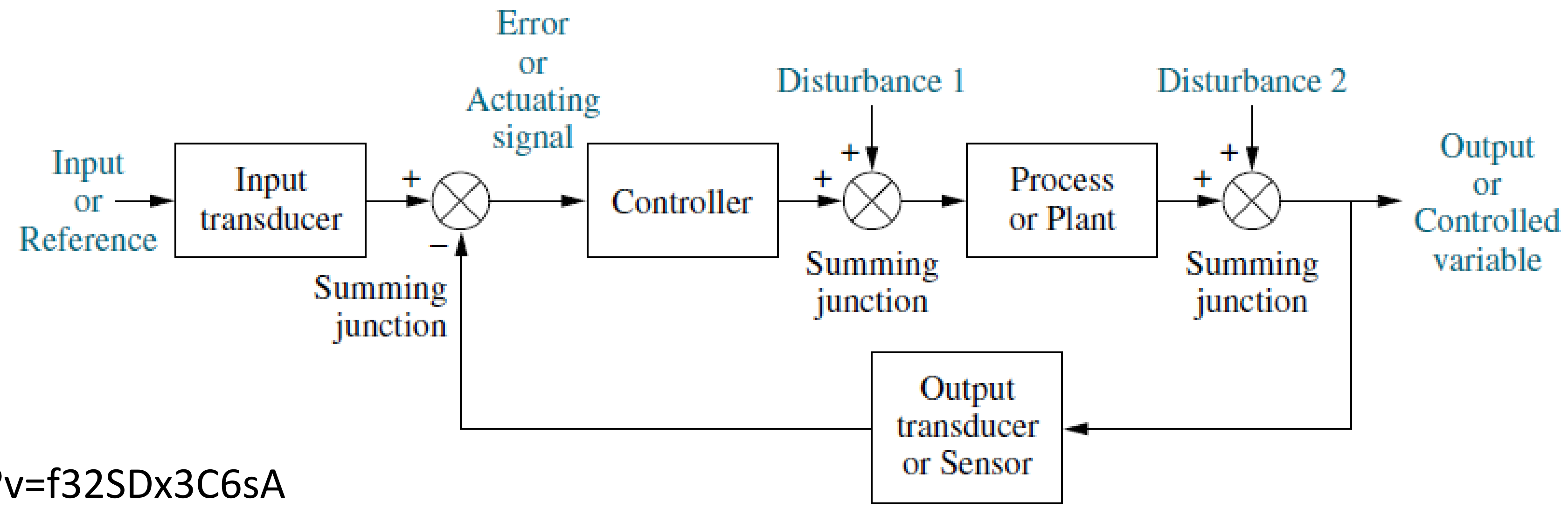
System Configurations

we discuss two major configurations of control systems: **open loop** and **closed loop**

Open-Loop Systems



Closed-Loop Systems (Feedback Control)



https://www.youtube.com/watch?v=f32SDx3C6sA

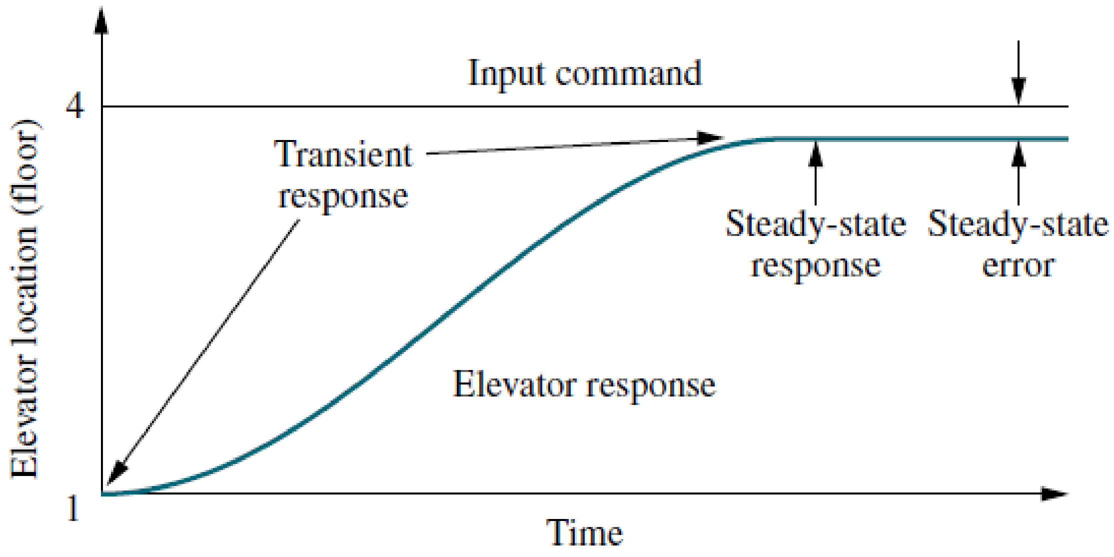
Analysis and Design Objectives

Analysis is the process by which a system's performance is determined. For example, we evaluate its transient response and steady-state error to determine if they meet the desired specifications.

Design is the process by which a system's performance is created or changed.

For example, if a system's transient response and steady-state error are analysed and found not to meet the specifications, then we change parameters or add additional components to meet the specifications.

A control system is ***dynamic***: It responds to an input by undergoing a transient response before reaching a steady-state response that generally resembles the input.



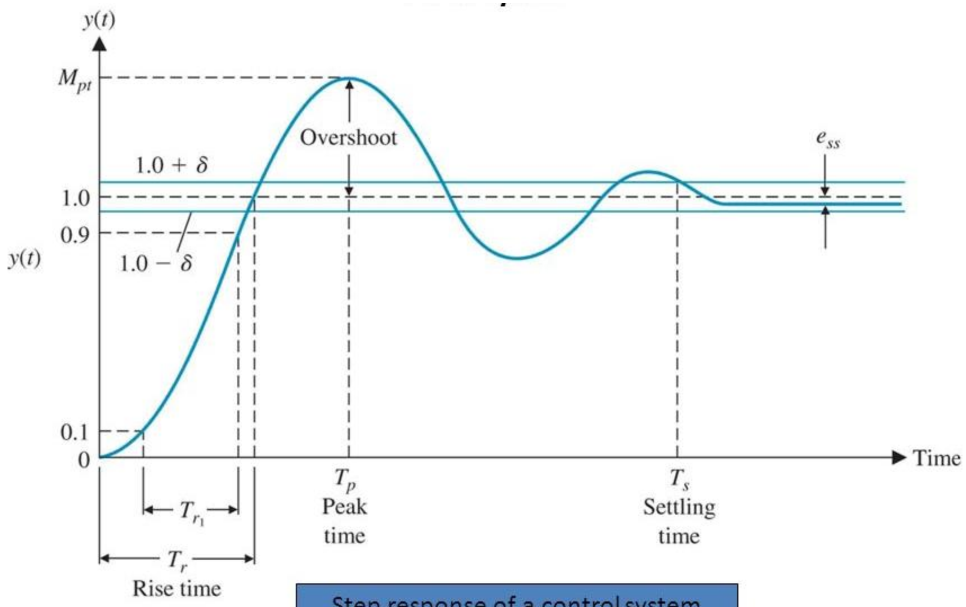
Dynamic behaviour

Transient Response

In electrical engineering and mechanical engineering, a **transient response** is the **response** of a system to a change from an equilibrium state.

Steady-State Response

A *steady-state response* is the behaviour of a system after a *long* time when steady conditions have been reached after an external excitation.



Step response of a control system

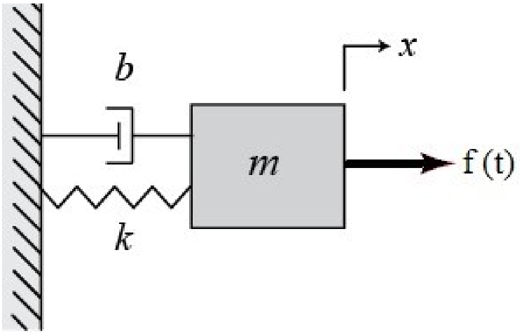
Stability

Discussion of transient response and steady-state error is smooth if the system does not have **stability**.

the total response of a system is the sum of

- the natural response
- and the forced response.

For linear differential equations, **homogeneous** and the **particular solutions**, respectively.



$$m\frac{d^2x}{dt} = F - b\frac{dx}{dt} - kx$$

Natural response describes the way the system dissipates or acquires energy. The form or nature of this response is dependent only on the system, not the input.

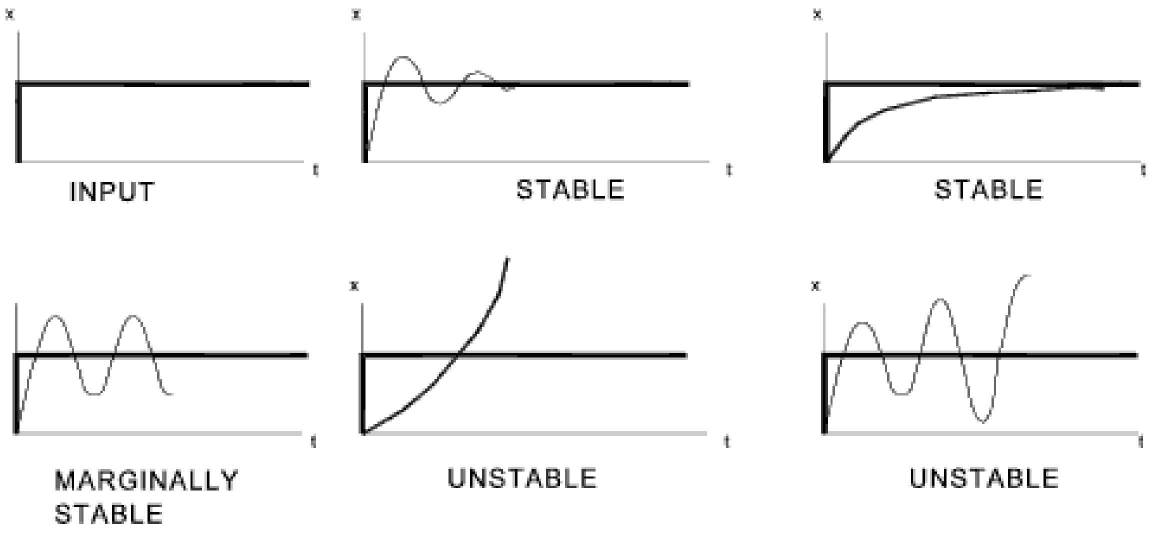
On the other hand, the form or nature of the **forced response** is dependent on the input.

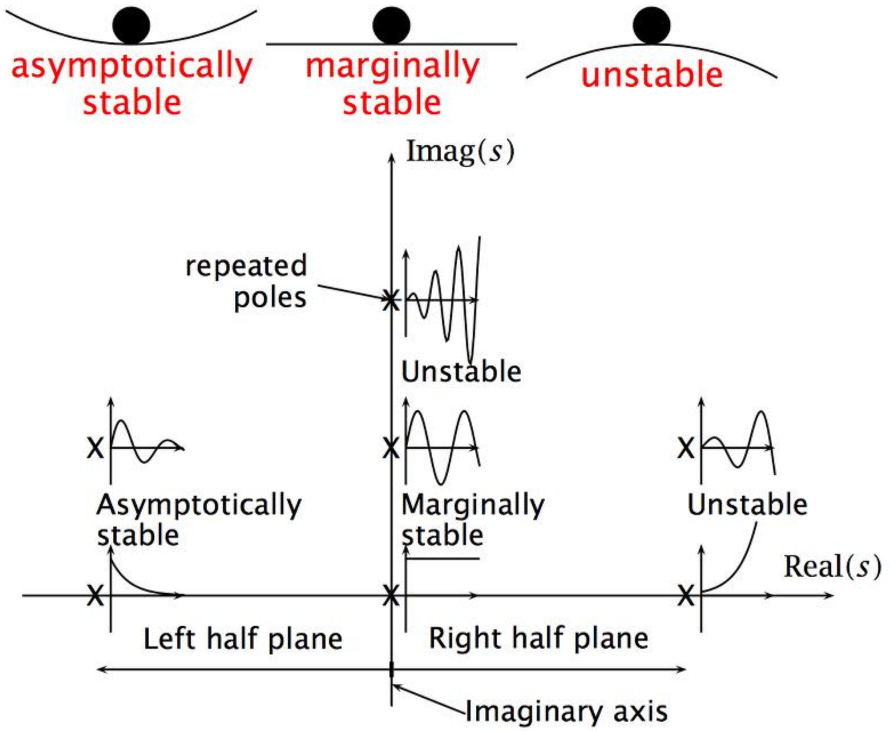
Thus, for a linear system, we can write

$$\boxed{\text{Total response} = \text{Natural response} + \text{Forced response}}$$

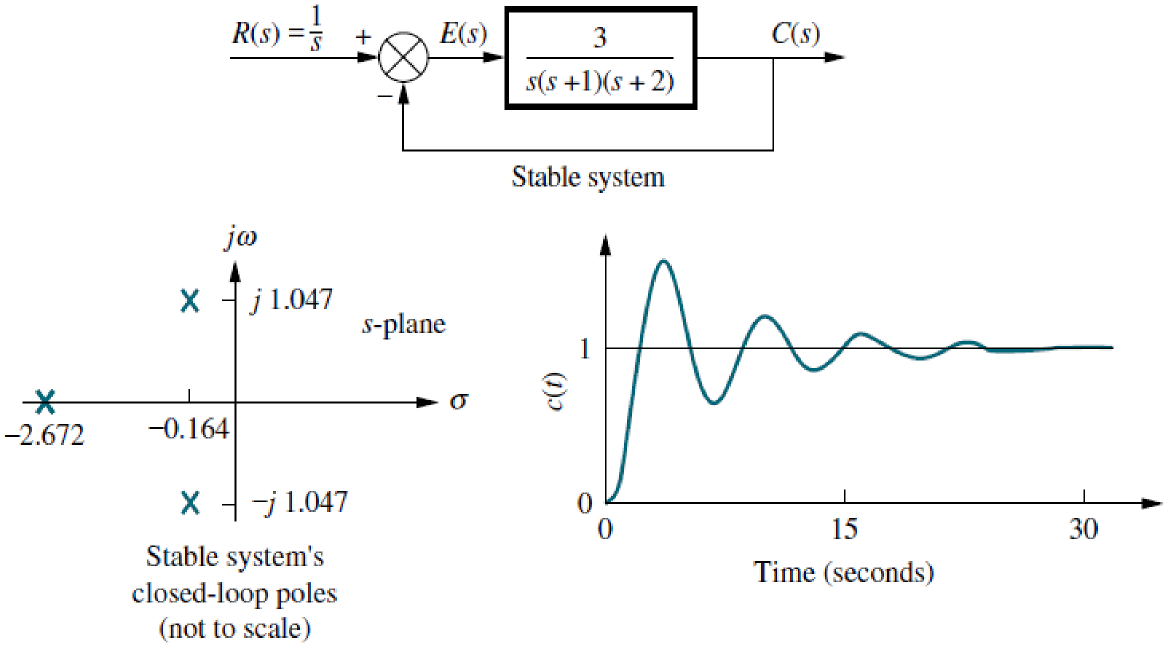
Stability

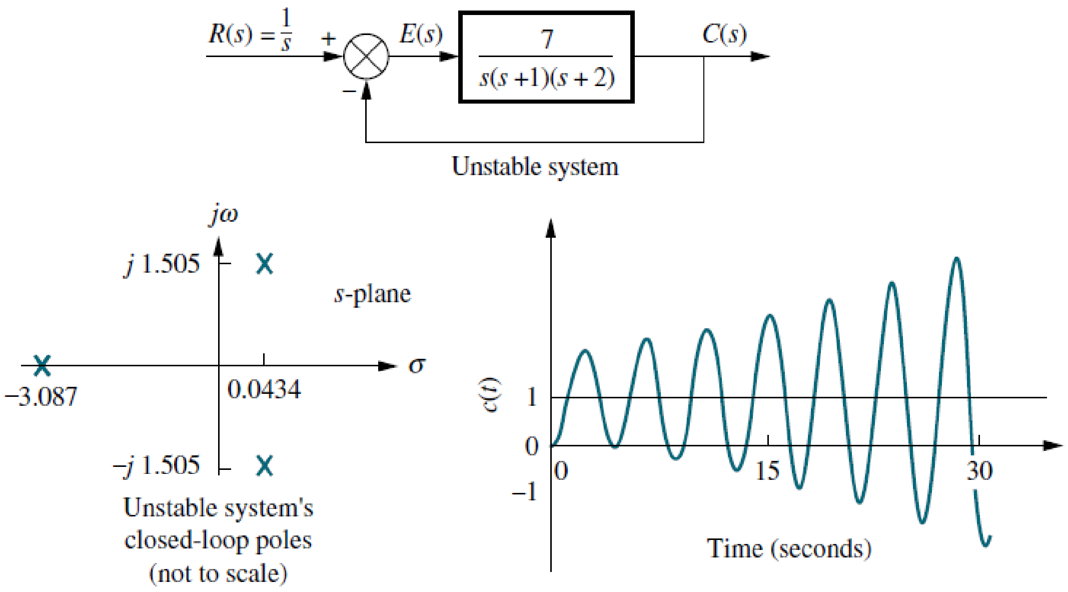
For a control system to be useful, the response must
(1) Eventually approach zero, thus leaving only the forced response, or
(2) oscillate.
(3) In some systems, however, the natural response grows without bound rather than diminish to zero or oscillate



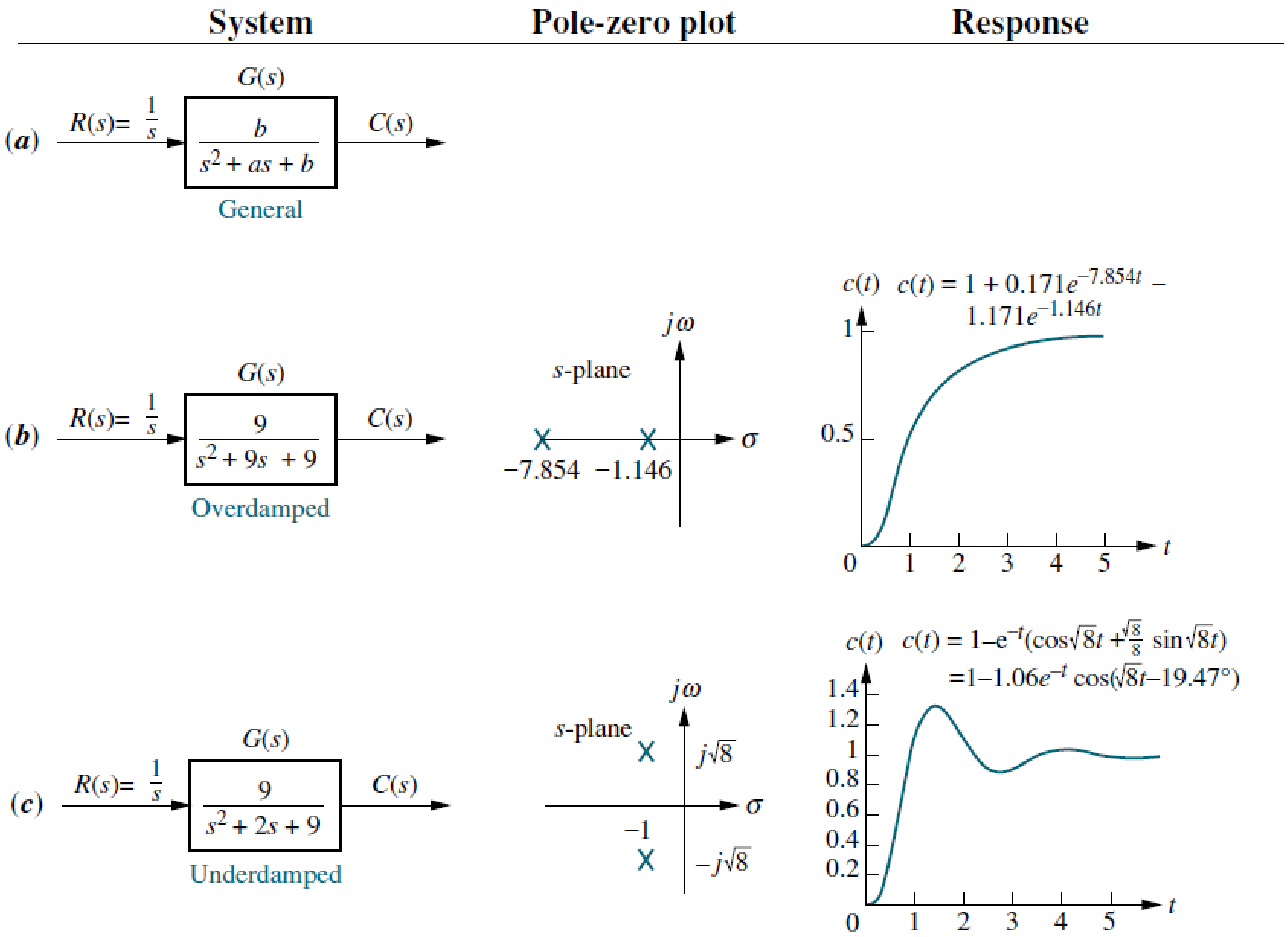


Stability


$R(s) = \frac{1}{s}$
+
−
$E(s)$
$\frac{3}{s(s+1)(s+2)}$
$C(s)$
Stable system
$j\omega$
$j\,1.047$
$-j\,1.047$
s-plane
σ
−2.672
−0.164
Stable system's
closed-loop poles
(not to scale)
$c(t)$
1
0
0
15
30
Time (seconds)

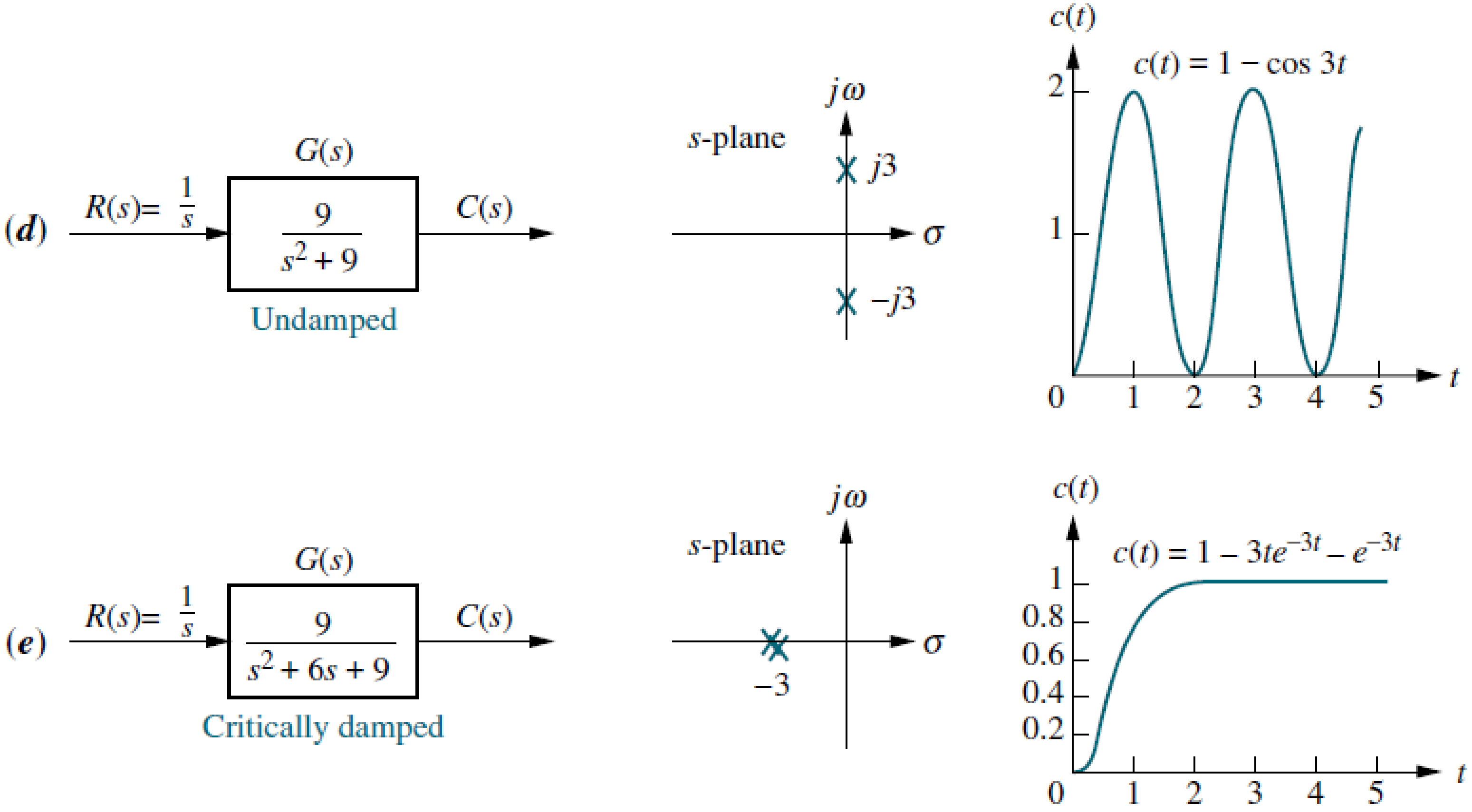

$R(s) = \frac{1}{s}$
+
−
$E(s)$
$\frac{7}{s(s+1)(s+2)}$
$C(s)$
Unstable system
$j\omega$
$j\,1.505$
$-j\,1.505$
s-plane
σ
−3.087
0.0434
Unstable system's
closed-loop poles
(not to scale)
$c(t)$
1
0
−1
0
15
30
Time (seconds)

Stability



System
Pole-zero plot
Response
(a)
$R(s) = \frac{1}{s}$
$G(s)$
$\frac{b}{s^2 + as + b}$
$C(s)$
General
(b)
$R(s) = \frac{1}{s}$
$G(s)$
$\frac{9}{s^2 + 9s + 9}$
$C(s)$
Overdamped
$j\omega$
s-plane
σ
-7.854
-1.146
$c(t)$
$c(t) = 1 + 0.171e^{-7.854t} - 1.171e^{-1.146t}$
1
0.5
0
1
2
3
4
5
t
(c)
$R(s) = \frac{1}{s}$
$G(s)$
$\frac{9}{s^2 + 2s + 9}$
$C(s)$
Underdamped
$j\omega$
s-plane
$j\sqrt{8}$
σ
-1
$-j\sqrt{8}$
$c(t)$
$c(t) = 1 - e^{-t}(\cos\sqrt{8}t + \frac{\sqrt{8}}{8}\sin\sqrt{8}t)$
$= 1 - 1.06e^{-t}\cos(\sqrt{8}t - 19.47°)$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
t

Stability


(d)
R(s)= 1/s
G(s)
9 / (s^2 + 9)
C(s)
Undamped
s-plane
jω
j3
σ
−j3
c(t)
c(t) = 1 − cos 3t
2
1
0
1 2 3 4 5
t
(e)
R(s)= 1/s
G(s)
9 / (s^2 + 6s + 9)
C(s)
Critically damped
s-plane
jω
σ
−3
c(t)
c(t) = 1 – 3te^−3t – e^−3t
1
0.8
0.6
0.4
0.2
0
1 2 3 4 5
t

Other Considerations

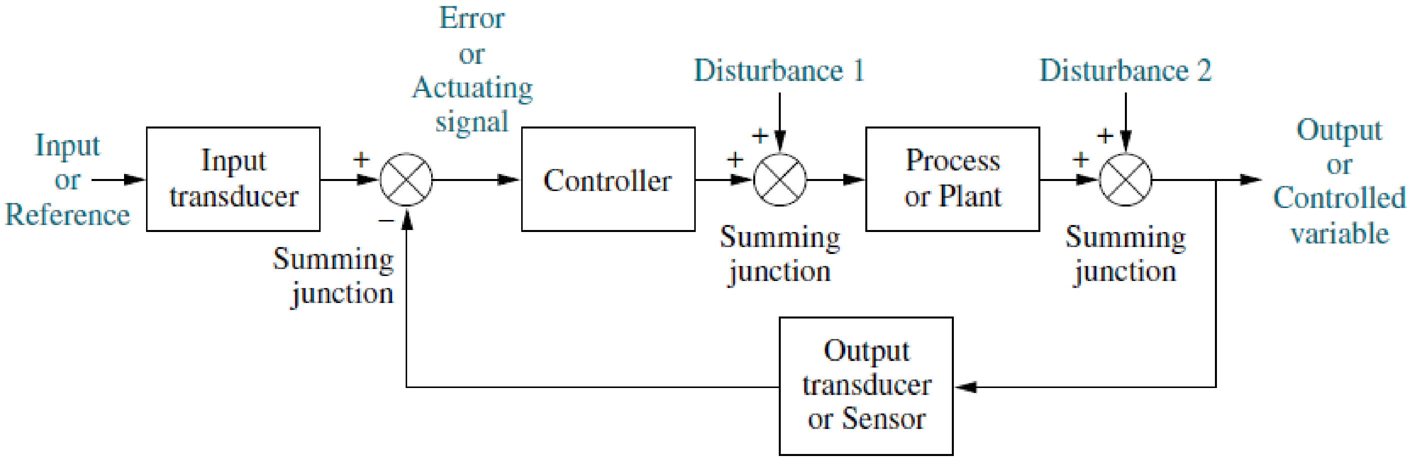
Another consideration is **robust design (parameter changes)**.

System parameters considered constant during the design for transient response, steady-state errors, and stability change over time when the actual system is built.

Thus, the performance of the system also changes over time and will not be consistent with your design.

Unfortunately, the relationship between parameter changes and their effect on performance is not linear.

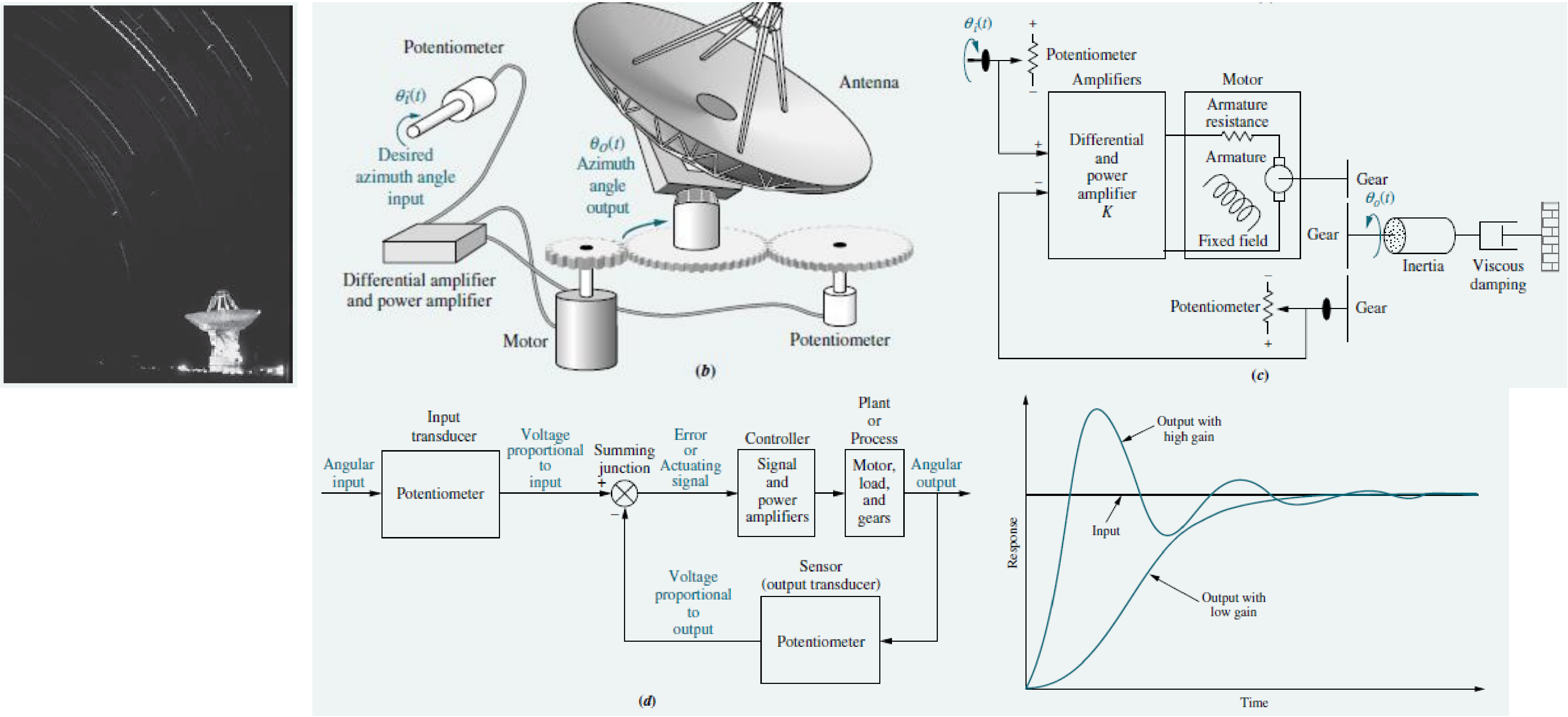
Thus, the engineer wants to create a robust design so that the system will not be sensitive to parameter changes.



Case Study

Antenna Azimuth: An Introduction to Position Control Systems

A position control system converts a position input command to a position output response. Position control systems find widespread applications in antennas, robot arms, and computer disk drives.



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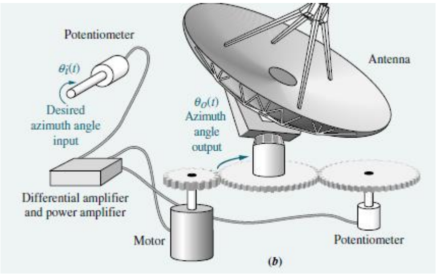
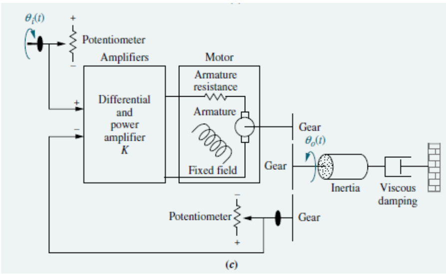
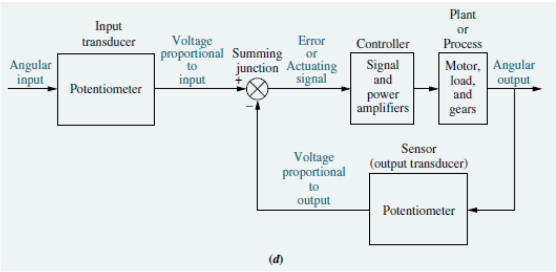
The Design Process

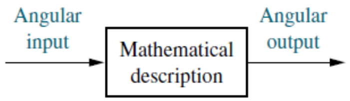
We establish an orderly sequence for the design of feedback control systems that will be followed as we progress through the rest of the course

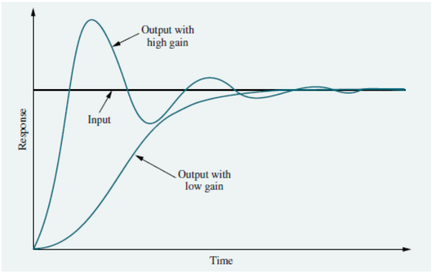
- **Step 1**: Determine a physical system and specifications from the requirements.
- **Step 2**: Draw a functional block diagram.
- **Step 3**: Transform the physical system into a schematic.
- **Step 4**: Use the schematic to obtain a block diagram, signal-flow diagram, or state-space representation.
- **Step 5**: If multiple blocks, reduce the block diagram to a single block or closed-loop system.
- **Step 6**: Analyze, design, and test to see that requirements and specifications are met.











Develop a Mathematical Model (Block Diagram)

Once the schematic is drawn, the designer uses physical laws, such as **Kirchhoff's laws** for electrical networks and **Newton's law** for mechanical systems, along with simplifying assumptions, to model the system mathematically.

Kirchhoff's voltage law	The sum of voltages around a closed path equals zero.
Kirchhoff's current law	The sum of electric currents flowing from a node equals zero.
Newton's laws	The sum of forces on a body equals zero;[3] the sum of moments on a body equals zero.

Kirchhoff's and Newton's laws lead to mathematical models that describe the relationship between the input and output of dynamic systems.
One such model is the linear, time-invariant differential equation,

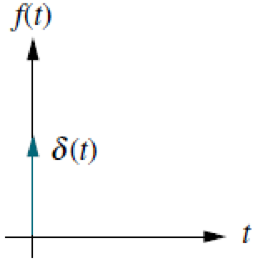
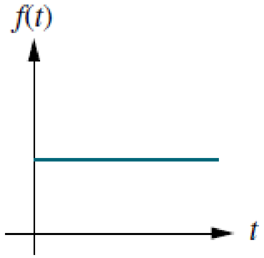
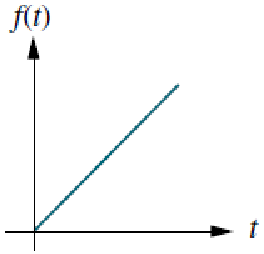
$$\frac{d^m c(t)}{dt^n} + d_{n-1}\frac{d^{m-1}c(t)}{dt^{n-1}} + \cdots + d_0 c(t) = b_m \frac{d^m r(t)}{dt^m} + b_{m-1}\frac{d^{m-1}r(t)}{dt^{m-1}} + \cdots + b_0 r(t)$$

Many systems can be approximately described by this equation, which relates the output, *c(t)*, to the input, *r(t),* by way of the system parameters, d_i and b_j.

Analyse and Design

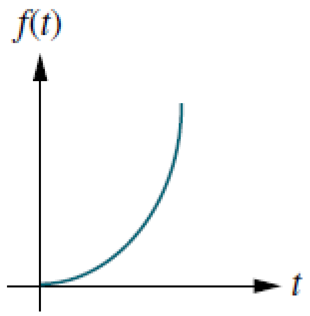
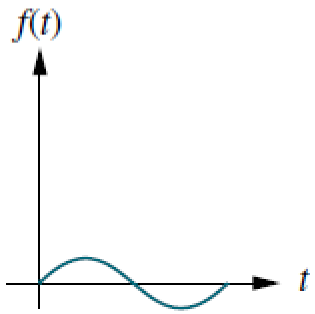
In this phase, the engineer analyzes the system to see if the response specifications and performance requirements can be met by simple adjustments of system parameters. If specifications cannot be met, the designer then designs additional hardware in order to effect a desired performance.

Test waveforms used in control systems

Input	Function	Description	Sketch	Use
Impulse	$\delta(t)$	$\delta(t) = \infty$ for $0- < t < 0+$ $= 0$ elsewhere $\int_{0-}^{0+} \delta(t)dt = 1$		Transient response Modeling
Step	$u(t)$	$u(t) = 1$ for $t > 0$ $= 0$ for $t < 0$		Transient response Steady-state error
Ramp	$tu(t)$	$tu(t) = t$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error

Analyse and Design

Test waveforms used in control systems

Input	Function	Description	Sketch	Use
Parabola	$\frac{1}{2}t^2u(t)$	$\frac{1}{2}t^2u(t) = \frac{1}{2}t^2$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Sinusoid	$\sin \omega t$			Transient response Modeling Steady-state error

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The End