SEE 2113
<u>CONTROL: MODELLING AND SIMULATION</u>

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OBJECTIVE: ***To help the students understand the basic concept of control system***

WEBSITE: ***http://elearning.utm.my***

SYLLIBUS:
1 Introduction to control systems
2 Mathematical modeling
3 System representation
4 Time domain response analysis
5 Introduction to computer simulation

ASSESSMENT:

Test 1	**:**	***15%***
Test 2	**:**	***15%***
Assignment + Tut	**:**	***20%***
Final Exam	**:**	***50%***

REFERENCES:
- ***Notes given in class or provided in website***
Brief notes on SEE2113, Shaharum Sulaiman
Control Systems Engineering, 2008. N.S. Nise
Modern Control Engineering, 1997. K.Ogata
Modern Control Systems. R. C. Dorf & R. H. Bishop

CHAPTER 1: INTRODUCTION

A) <u>Introduction</u>

- **Control systems are important and are present almost everywhere in our daily lives**
- **Examples of man-made control systems: CD player, radio antenna, rockets/missiles, robots, oven, room air condition**
- **Examples of God-created control systems: level of adrenalin in the human body, entry of light through the human eye, holding and carrying things using hands, human riding a bicycle**
- **Malfunction of control systems: accidents (e.g: alcohol), difficulties (e.g: water toilet pumps)**
- **Control engineers: are normally involved at the highest level in a particular project, determining the suitable system performance, functions of subsystems and their interconnections (interfacing needs, hardware and software design, testing and simulation)**
- **Control engineers: are involved in several fields of science and technology, and are normally required to communicate with experts in other fields**

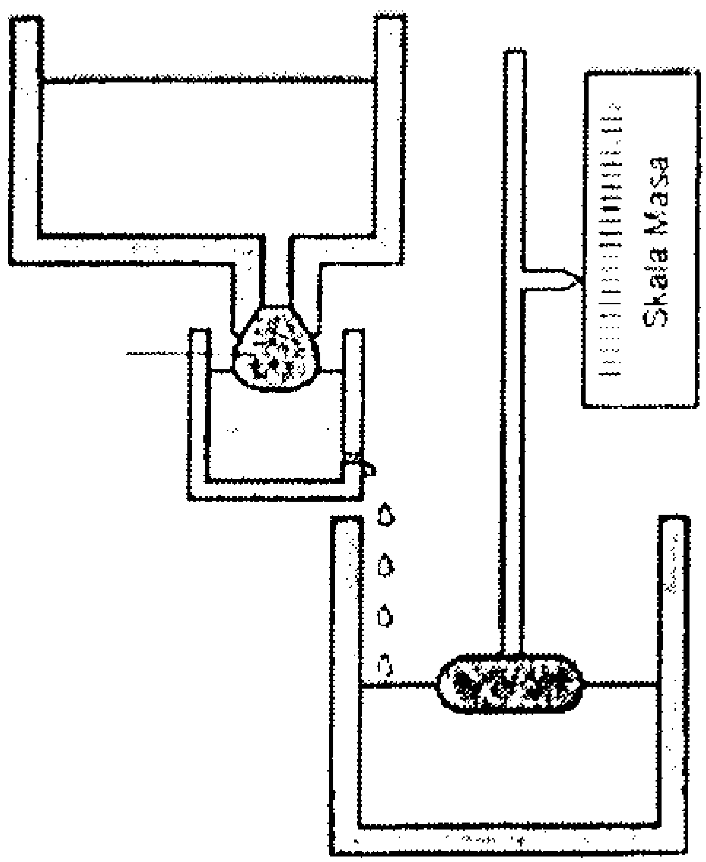
B) <u>Benefit or use of control systems</u>

- ***Power amplifications*: With control systems, heavy things can be moved precisely (e.g: using robots, etc)**
- ***Convenience*: Operators only need to push buttons to move things**
- ***Remote control*: Robots are always used for dangerous operations such as moving radioactive objects or bombs**
- ***Noise filtering*: Control systems are always faced with unwanted signals/noise. For example, an aeroplane in a level flight is faced with air turbulence. The aeroplane control systems can keep the aeroplane on its course by filtering the 'noise' caused by the air turbulence.**

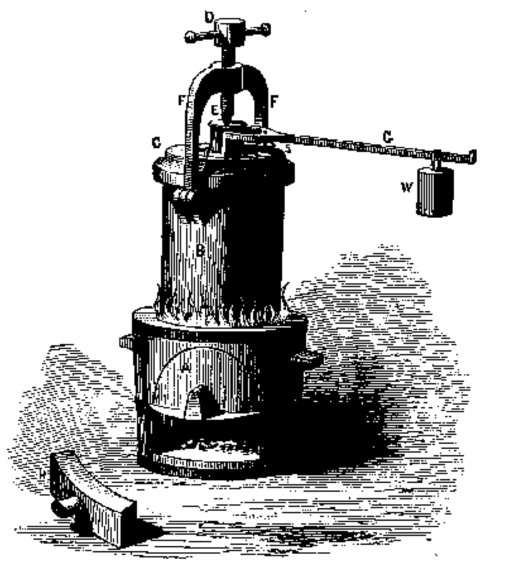
- *Repetition*: **Control systems can be used continuously for a long period of time.**

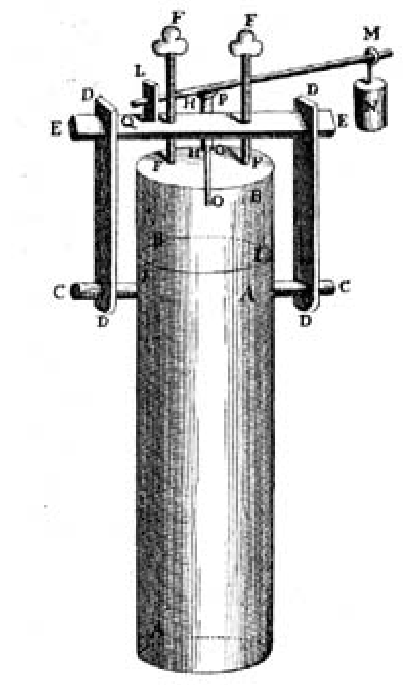
C) <u>History of control systems</u>

- **One of the earliest control systems known is the water clock invented by Ktesibios in 300 BC which is shown below**



- **In 1681, Denis Papin introduced the steam pressure control systems, where he invented the safety valve (very similar to the present pressure cooker)**





- **During the same century, Cornelis Drebbel of Holland invented a control system to regulate temperature for hatching chicken eggs**
- **On the following century, Edmund Lee was able to control the speed of a windmill while James Watt invented the fly-ball speed governor to control the speed of a steam engine**
- **The field of classical control systems known today began in the later half of the mid 19th century when J.C. Maxwell wrote about the stability of 3rd order systems based on the coefficients of the differential equations**
- **In 1874, Edward John Routh, using the suggestion from William Kingdon Clifford was able to extend the stability criterion to the fifth order systems. In 1877, Routh submitted a paper entitled "A treatise on the stability of a given state of motion", which contains what is known as the Routh-Hurwitz criterion**
- **During the second half of the 1800s, the development of control systems focused on the steering and stabilizing of ships. In 1922,**

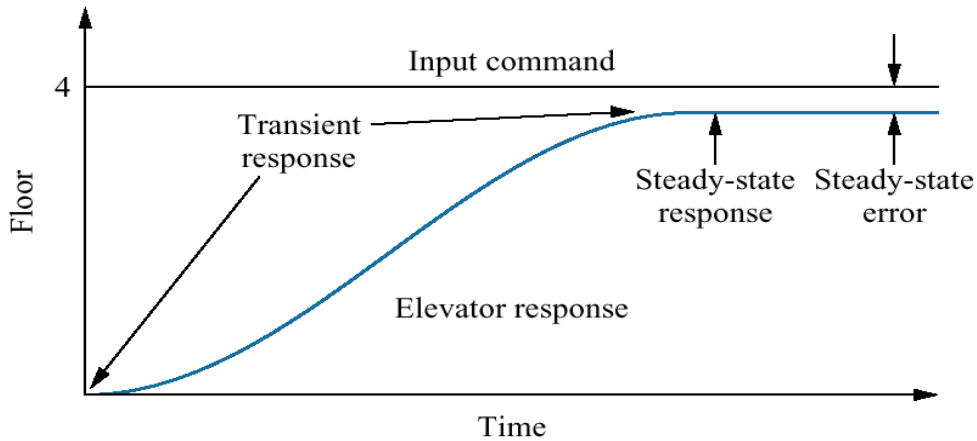
the Sperry Gyroscope Company installed an automatic steering system that used the elements of compensation and adaptive control to improve the performance

- **The general control theory was much influenced by N. Minorsky who introduced the PID controller in 1885**
- **In 1948, W.R. Evans who worked in the aircraft industry, developed a graphical technique for designing controllers, which is called the Root Locus technique**
- **Today, control systems find widespread applications, from the simplest household tools, to the most sophisticated military equipment such as fighter planes and orbital satellites**
- **Theories in the field on control systems are continuously being developed nowadays with the aid of advanced computer technology**

D) <u>Control system definition</u>

- **A control system provides an output or response for a given input or stimulus**
- **A controlled variable normally determines the input and output of a control system**

- **For example: Elevator button and the desired level (input), actual level of elevator (output)**

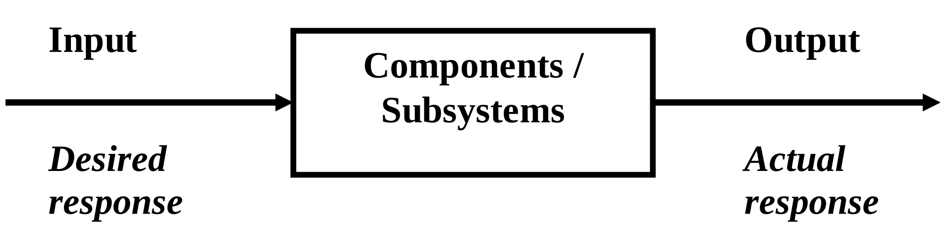


- **Input is the desired level**
- **Output is the actual elevator level (control variable)**

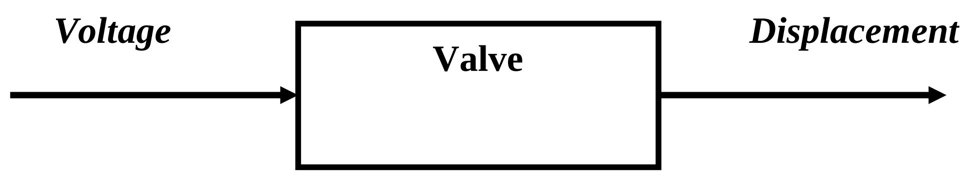
E) <u>Block diagrams</u>

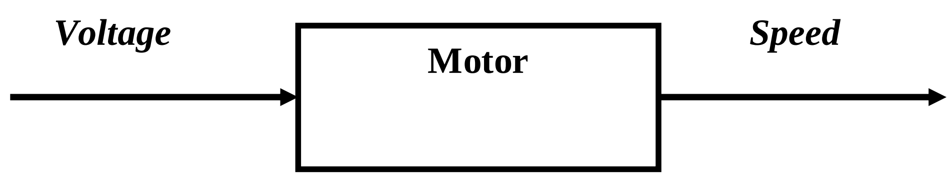
- **A Control System consists of subsystems and processes (or plants) that are interconnected to control the system output**
- **For a system having one or more components, it is easier to represent the components or the subsystems using block diagrams, where the signal transfer function can be visualized clearly**
- **3 main characteristics of Block Diagrams:**
  - **a. Fundamental blocks**
  - **b. Components/subsystems**
  - **c. Signals**

- **Fundamental blocks**



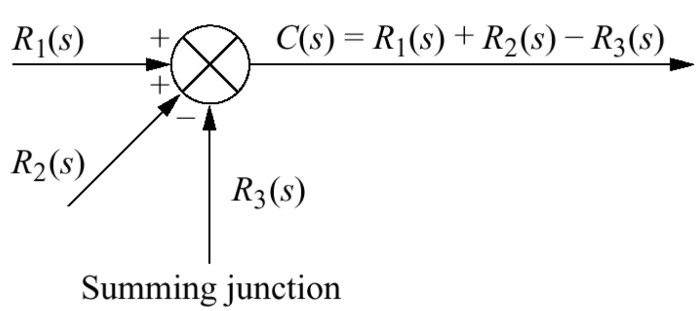
- Represents components or subsystems such as controller, amplifier, etc
- Each block may have one or more outputs
- The input and output signals may have the same form or they may be changed into a different form depending on the function of the component or subsystem
- Example:





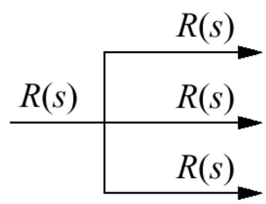
- **Components/subsystems**

  - **Summing junction**



allows 2 or more signals to be added/subtracted. The + and – signs indicate whether the signals are added or subtracted.

- **Take-off point**

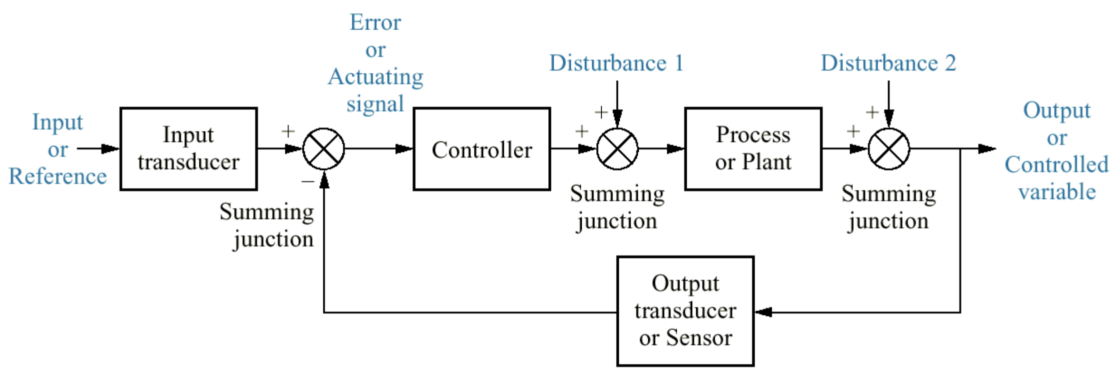


allows the signals to be taken from any component's output. Assuming that it does not 'load' any components output (the signals are not changed)

- **Controllers, plants**
- **Actuators**
- **Sensors**
- **Amplifiers**

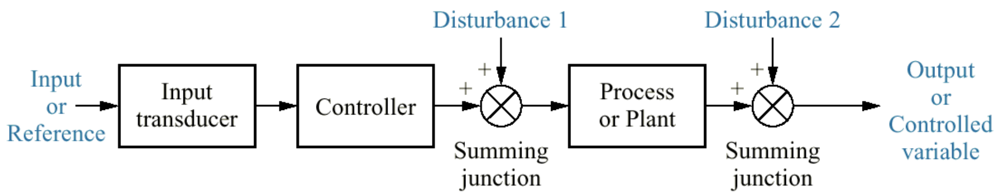
- **Signals in Control Systems**
  - **Input / reference [*r(t), R(s)*]**
  - **Output [*c(t), C(s)*]**
  - **Error [*e(t)=r(t)-c(t)*]**
  - **Feedback, disturbances / noise**

- **Example:**



F) <u>Open loop control systems (OLCS)</u>

- **The output signal of an OLCS is not fed back to influence the control action**



- **The control action of an OLCS depends only on the input signal**

- **OLCS are not capable of filtering disturbances or noise**

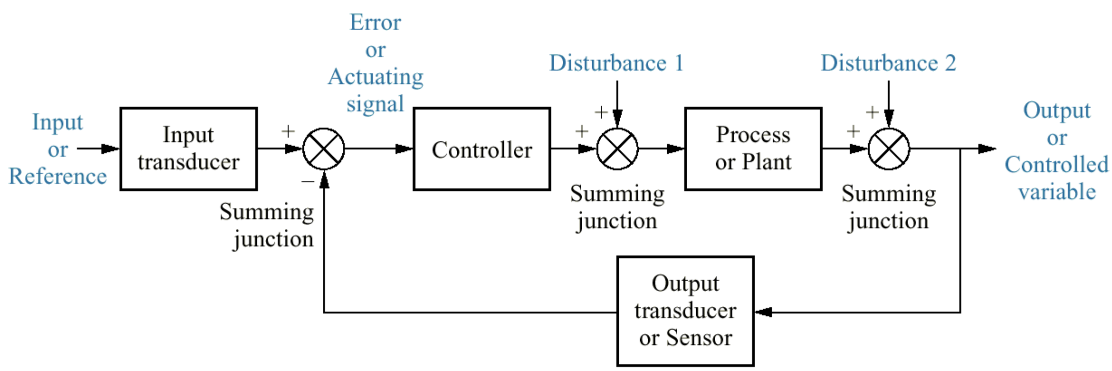
- **Examples: toaster, washing machine (the washing process), electric fan, rice cooker, photocopy machine, etc**

- **OLCS are suitable when input signal for satisfactory system performance can be estimated/approximated and does not change**

- **Advantages of OLCS are that its structure is simple compared to a closed loop control system and is cheaper to build.**

G) <u>Closed Loop Control Systems (CLCS)</u>

- **The output signal of a CLCS is fed back to influence the control action and improve the overall system performance**



The advantages of CLCS include:

- **Ability to compensate for / filter disturbances and/or noise**
- **Not sensitive to noise and changes to system parameters or environment**
- **Can be used repeatedly for a long period of time**
- **Easier to design a controller for a CLCS to achieve the desired transient and steady state response**

- **Examples: position control systems (robot arms), velocity control systems (vehicle cruise control), temperature control systems (air-conditioner)**

- **However, in practical control systems, a combination of both OLCS and CLCS is normally used.**

- **A simple example is the washing machine: the process of filling up the tank with water is a CLCS operation, while the process of washing and rinsing is an OLCS operation.**

H) <u>Transfer Function</u>

- **A control system with input *r(t)* and output *c(t)* can be represented using a differential equation:**

$$a_n \frac{d^n c(t)}{dt^n} + a_{n-1} \frac{d^{n-1} c(t)}{dt^{n-1}} + ... + a_0 c(t) = b_m \frac{d^m r(t)}{dt^m} + b_{m-1} \frac{d^{m-1} r(t)}{dt^{m-1}} + ... + b_0 r(t)$$

- **This time domain equation can be transformed into an equation in the Laplace domain using Laplace Transforms:**

$$L[f(t)] = \int_0^\infty e^{-st} f(t) dt = F(s)$$

- **The function *F(s)* is a function in the Laplace domain where *s* is a complex number :**

$$s = \alpha + j\omega$$

- **The differential equation that has been mapped to the Laplace domain can be written as:**

$$a_n s^n C(s) + a_{n-1} s^{n-1} C(s) + ... + a_0 C(s) = b_m s^m R(s) + b_{m-1} s^{m-1} R(s) + ... + b_0 R(s)$$

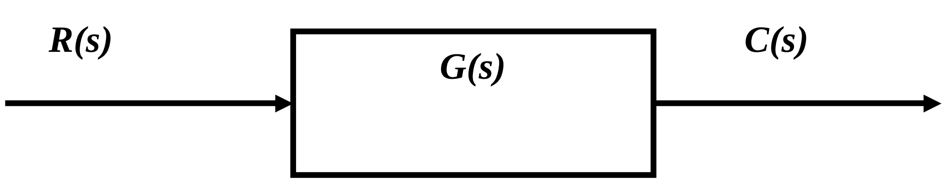
- **The same equation can be re-written as:**

$$\frac{C(s)}{R(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + ... + b_0}{a_n s^n + a_{n-1} s^{n-1} + ... + a_0} = G(s)$$

- **The input and the output has been separated although still related using an equation**

- **This equation, *G(s),* is called the transfer function**

- **The transfer function can also be represented using a block diagram:**



- $C(s) = G(s)R(s)$ **or** $G(s) = \dfrac{C(s)}{R(s)}$

- ***G(s)*** **is also the open loop transfer function in this case**

- **Important terms/definitions:**

$$G(s) = \frac{s^2 + 4s + 3}{s^5 + 8s^4 + 20s^3 + 16s^2}$$

Zeros (-1, -3)

order

$$G(s) = \frac{(s+1)(s+3)}{s^2(s+2)^2(s+4)}$$

type

Poles (0, 0, -2, -2, -4)

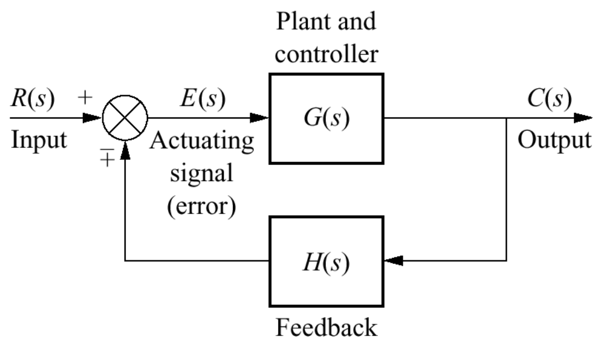
- **For a 2nd order system:**

$$G(s) = \frac{\omega_n^{\,2}}{s^2 + 2\zeta\omega_n s + \omega_n^{\,2}}$$

where ω_n **= natural frequency**

ζ **= damping ratio**

- **The closed loop transfer function:**



E(s) = R(s) - H(s)C(s) **and** ***C(s) = G(s)E(s)*** **giving**

C(s) = G(s)[R(s) - H(s)C(s)] **and by re-arranging gives**

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 \pm G(s)H(s)}$$

which is the closed loop transfer function

I) <u>The effects of feedback on open loop systems</u>

- **Feedback is used to reduce the error between the input and output of the system**

- **It effects the system performance characteristics such as stability, overall system gain, sensitivity and bandwidth**

- **Effect on the system sensitivity**

  - **Feedback can make the system's response less sensitive to external disturbances, parameter changes and noise**

- **Effect on the system stability**

  - **An unstable system can be stabilized using feedback**

  - **Stability refers to the ability of a system to follow its input signal**

- **A system that cannot control its output, or its output increases infinitely is an unstable system**

- **However, by adding feedback may also cause instability to an already stable system**

- **Effect on the system gain**

  - **A feedback influences system's transfer function and consequently, the overall system gain**

  - **The letter '*s*' in the Laplace domain represents a complex number**

  - **Therefore, the system's gain can be obtained by finding the magnitude of the system's transfer function**

  - **In other words, the system gain =** $\left|\dfrac{C(s)}{R(s)}\right|$

  - **For the OLCS, its system gain =** $\left|\dfrac{C(s)}{R(s)}\right| = \left|G(s)\right|$

  - **For the CLCS, its system gain =** $\left|\dfrac{C(s)}{R(s)}\right| = \left|\dfrac{G(s)}{1 \pm G(s)H(s)}\right|$

  - **The system gain can be increased or decreased when adding the feedback depending on whether the feedback is + or -**

J) <u>Analysis and design objectives of control systems</u>

- **Control systems are dynamic. They respond to the input by going through a transient phase before settling to the steady state phase. Normally, we would like the steady state output signal to be the same as the input signal**

Initial value ➔ transient response ➔ steady state value

- **Three main objectives in designing a control system**

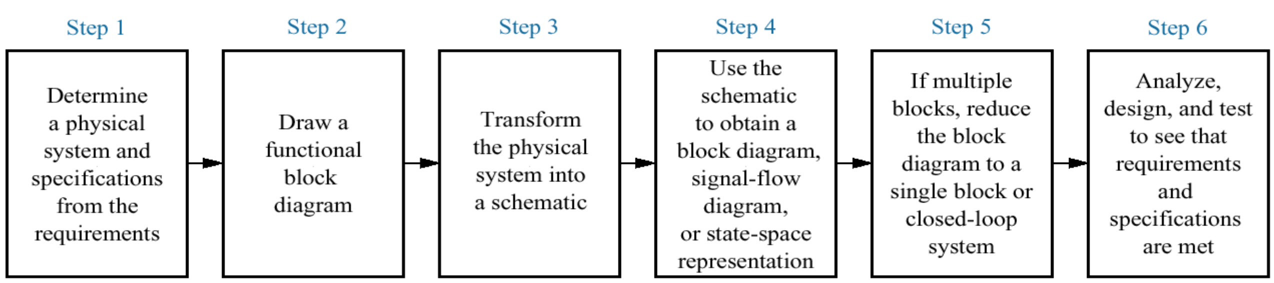
  - ***Transient response*: to make sure that the transient response of a control system is within the specification needed. For example, in an elevator operation, a very slow movement of the elevator could be a boring long travel for the people in a hurry, while a very fast movement could be uncomfortable for them.**

  - ***Stability*: to make sure that the system can produce consistent or steady output. An unstable system is harmful to the plant and may cause serious accidents**

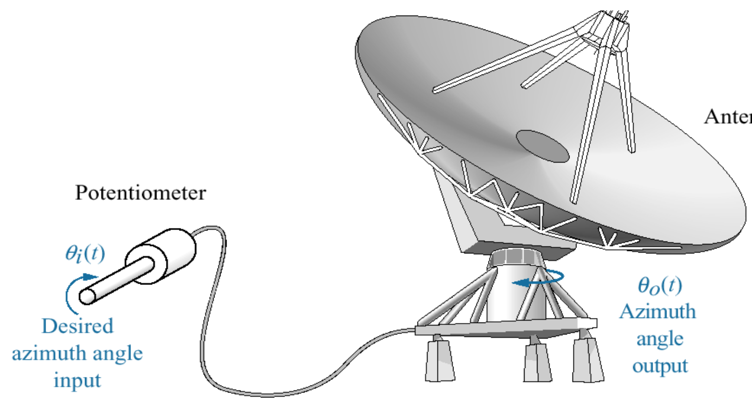
  - ***Steady state response*: steady state response only exists for stable systems. An important characteristic for design is the steady state error. Hence, the steady state error has to be as minimum as possible. Example, an elevator that does not stop at the same level at the floor may cause serious accidents to its passengers**

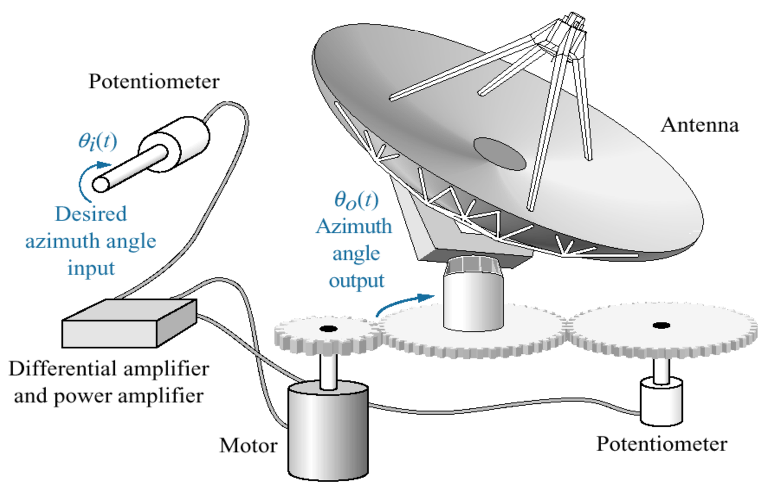
- **Other design objectives include the sensitivity to parameter changes and cost.**

- ***The design process of a control system*: A systematic design process has to go through a sequence of steps to achieve the objectives or specifications**

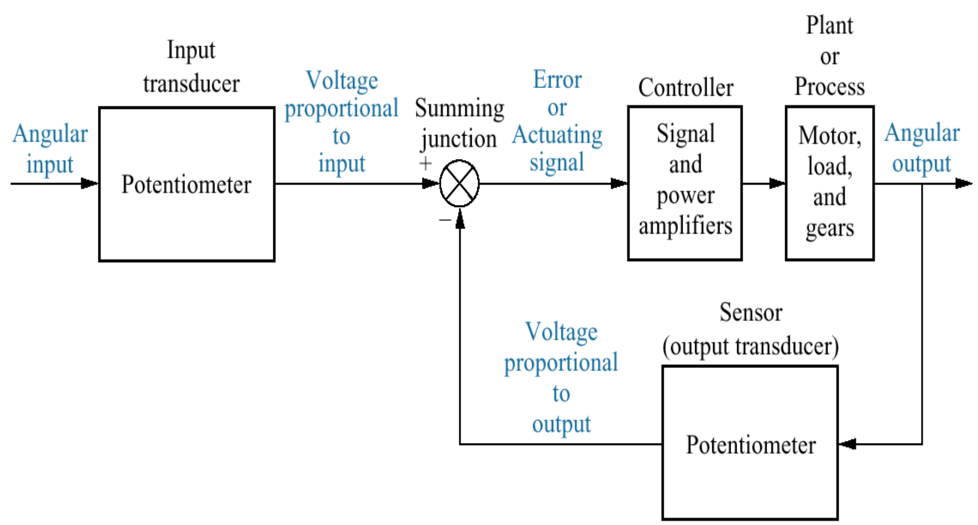


- ***Step 1*: Transforming the requirements into physical system and design specifications. For example, in the antenna azimuth position control system, the requirement would state the desire to position the antenna from a remote location and describe such features as weight and physical dimensions. Using the requirements, the design specification such as the desired transient response and steady-state accuracy are determined.**

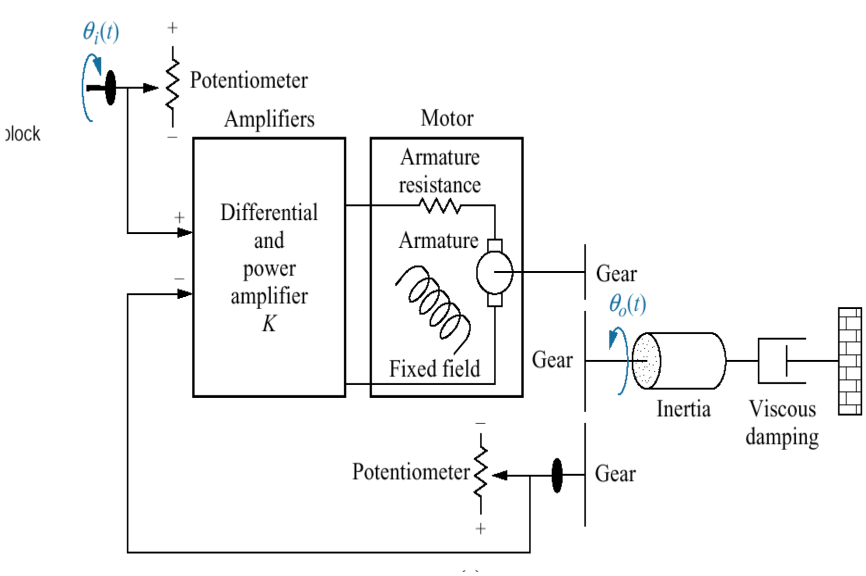




- ***Step 2*: At this step, the designer will interconnect the relation between system components, such as electrical components and mechanical components**



- ***Step 3*: Schematic diagram displays further information on the components used.**



- ***Step 4*: *The development of a mathematical modeling*. The schematic diagram helps the development of mathematical model for the system. Physical laws such as Kirchhoff's laws for electrical networks, Newton's laws for mechanical systems, along with simplifying assumptions, are used to model the system mathematically. The mathematical model can be of several forms such as differential equations, transfer functions and state-space equations.**

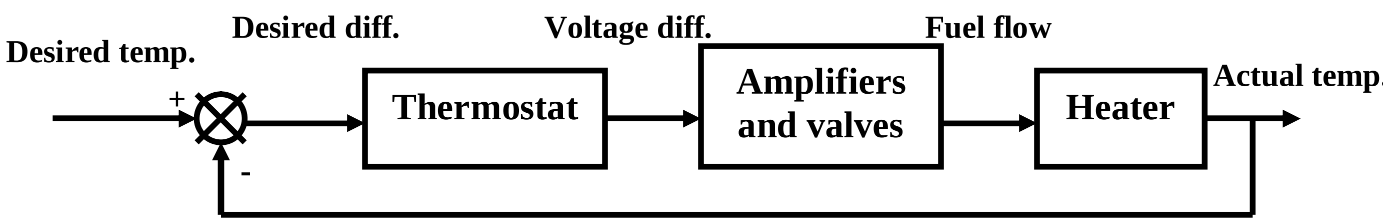
- ***Step 5*: *Block diagram reduction*. Normally, a practical system has complex structure. Hence, the block diagram algebra and the signal flow graph methods (among others) are used to simplify the block diagram structure of the system.**

- ***Step 6*: *Analysis and design*. At this stage, the designer has to analyze and evaluate the system specification. In some cases, a simple gain adjustment would solve the problem of getting the required performance. On the other hand, in most cases, controllers and compensator in many forms need to be designed.**

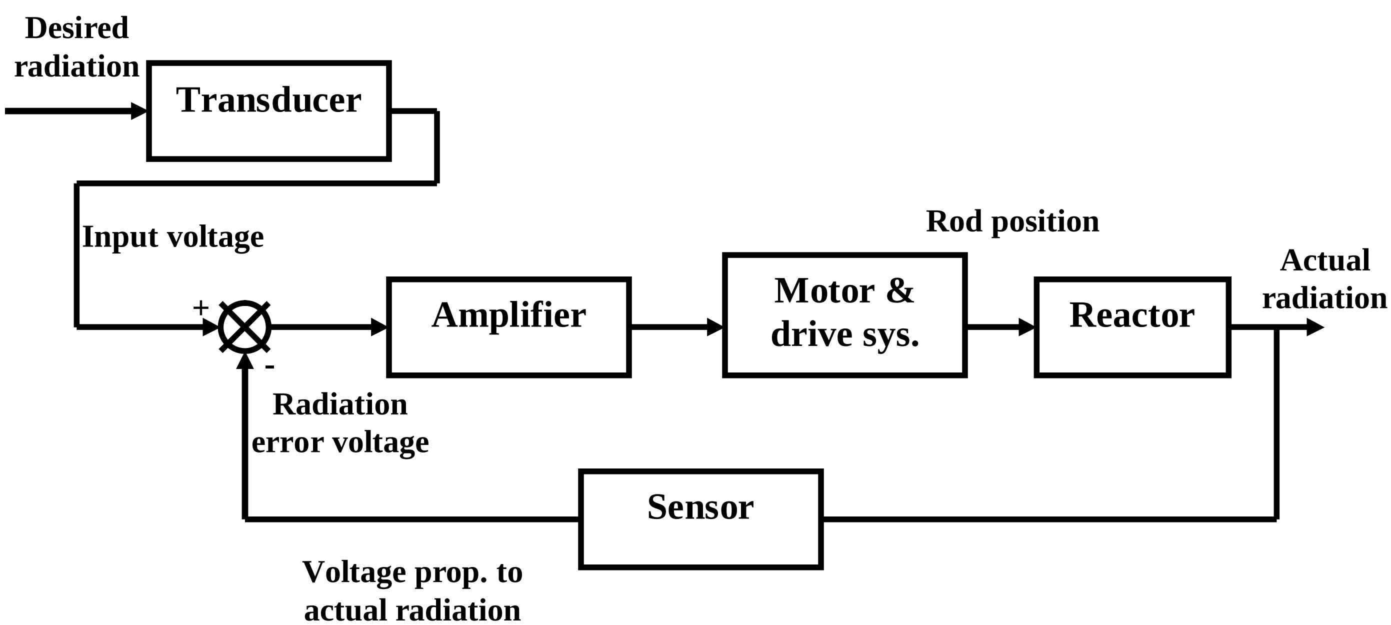
- ***Step 7*: *The development of system's prototyped*. For a real system, which needs might be expensive to build, a small system's prototyped could be build to analyze on its practical aspects. The real system can be build once any problems encountered are satisfactorily solved.**

K) **Examples of control systems**

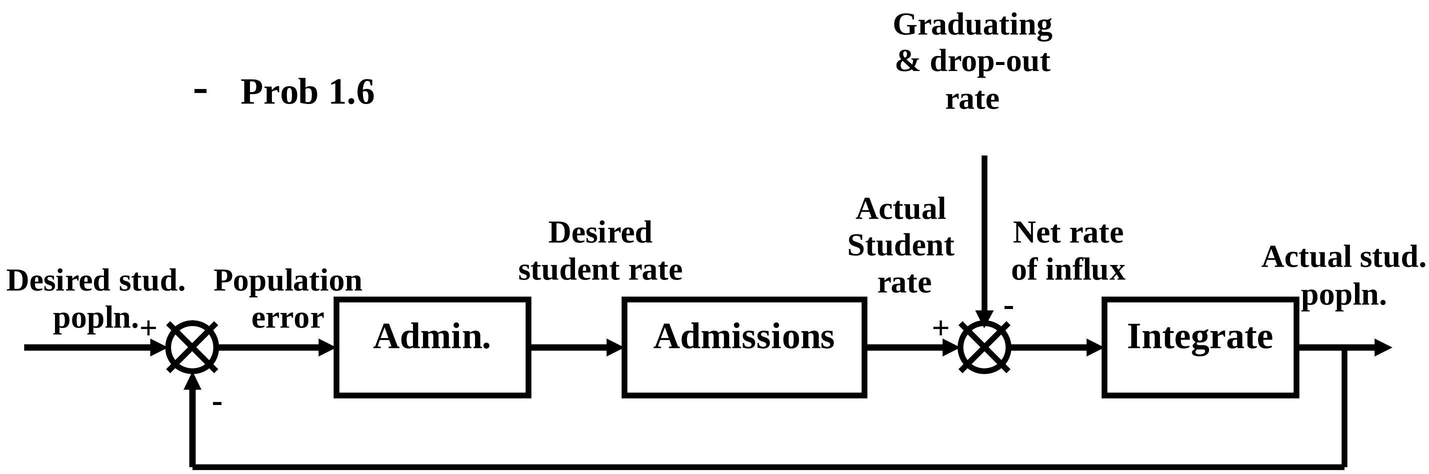
- **Prob 1.2**



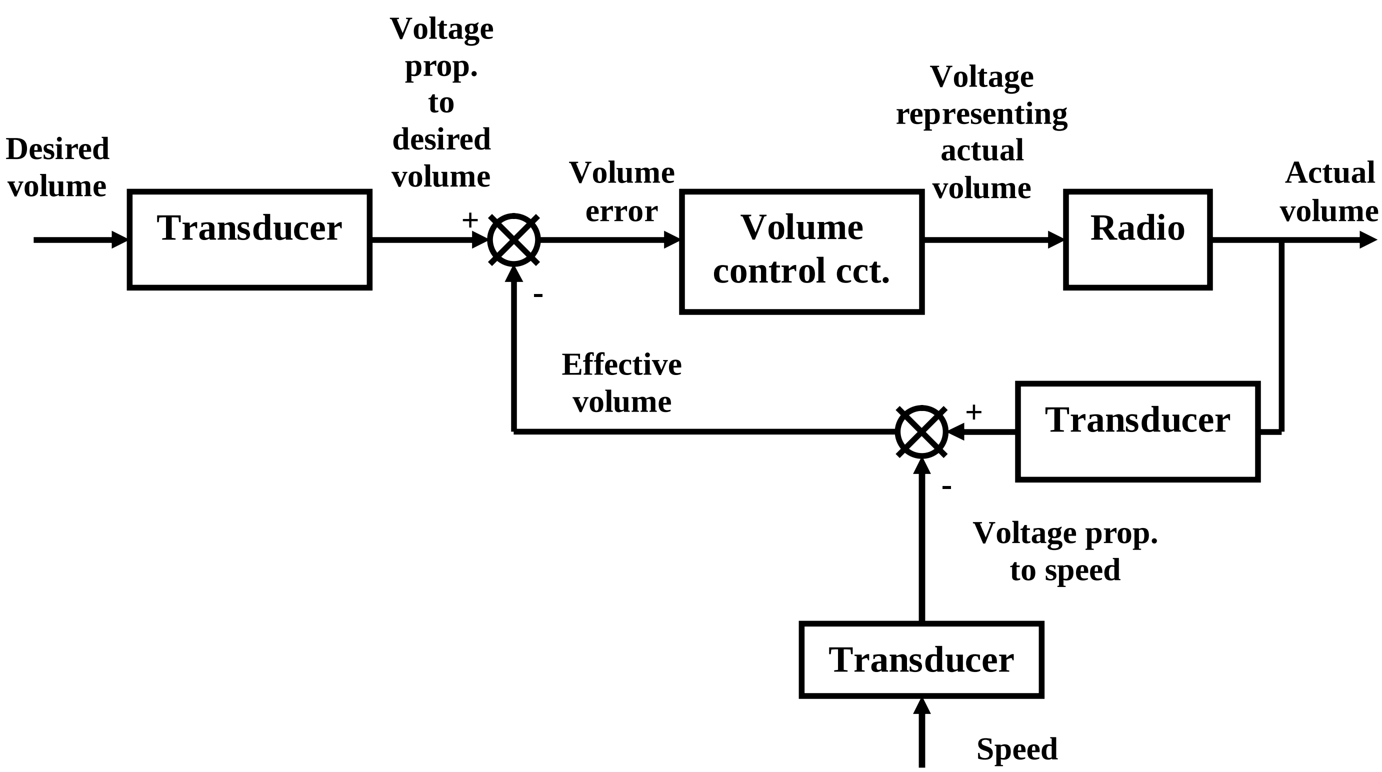
- **Prob 1.5**



- **Prob 1.6**



- **Prob 1.7**



L) <u>Classification of control systems</u>

- **A control system can be classified according to several criteria depending on the purpose of the system and the relevant classes it belongs to**

  1. **Classification based on type of *signals* used**

  - ***Continuous control systems*: signals that are used in subsystems and components in the control system is in time domain, *t*.**

  - ***Discrete type control systems*: signals that are used in subsystems and components in the control system is in discrete or digital form.**

  2. **Classification based on the *mathematical model* of the system**

  - ***Linear control systems***

    - **An ideal system**
    - **Is always used during the analysis and design phase**
    - **Several tool/techniques can be used to solve the control problems**
    - **Example: dc motor**

  - ***Non-linear control systems***

    - **Systems that normally exist in the real world**
    - **Difficult to analyze**
    - **No general method to find the control solution**
    - **Approximations are normally made so that the system behaves like a linear system to allow analysis and design**
    - **Example: ac motor, inverted pendulum**

- **Control systems can also be grouped into two groups**

  1. ***Kinetic (tracking)* control systems**

     - **Control variables: displacement/position, speed, acceleration**
     - **Fast system response with small delay time**
     - **Input may be fixed or changing**
     - **Normally involves electrical or hydraulic manipulators**

  2. ***Process (regulating)* control systems**

     - **Control variables: temperature, flow, level, pressure**
     - **Slow system response with large delay time**
     - **System responds to a fixed set point**
     - **Examples of manipulators include pneumatic manipulators or heating elements**

M) <u>Common terminology in control systems</u> (English ➔ Malay)

- ***Automatic*: Kawalan yang menggunakan peralatan yang beroperasi secara sendiri berdasarkan kaedah tertentu untuk menghasilkan sambutan yang dikehendaki.**

- ***Disturbance*: Isyarat yang tidak diingini yang berpunca dari dalaman atau luaran sistem. Ia mengganggu sistem dan memberikan kesan buruk terhadap isyarat keluaran sistem.**

- ***Plant*: Peralatan seperti gabungan komponen-komponen mesin yang digunakan untuk melaksanakan sesuatu kerja yang hendak dikawal.**

- ***Process*: Operasi yang berturutan dan berterusan yang menghasilkan perubahan antara satu operasi dengan operasi seterusnya. Kadangkala, istilah ini digunakan bagi loji.**

- ***Design*: Langkah-langkah mencipta komponen-komponen sistem. Setiap komponen tersebut mempunyai peranan tertentu dalam sistem keseluruhan.**

- ***Synthesis*: Langkah-langkah menggabungkan komponen-komponen sistem bagi menghasilkan sebuah sistem yang padu.**

- ***System*: Gabungan komponen-komponen yang beraksi bagi mencapai sesuatu tujuan. Ia terdiri daripada sistem fizikal (motor, ketuhar, dsb.) dan bukan fizikal (ekonomi, kemasukan pelajar ke universiti, dsb.)**

- ***Control system*: Gabungan komponen-komponen bagi membentuk sebuah sistem yang menghasilkan keluaran yang dikehendaki.**

- ***Open-loop control sistem*: Sistem yang menggunakan alat untuk mengawak proses tanpa menggunakan suapbalik. Oleh itu, isyarat keluaran tidak mempengaruhi tindakan kawalan sistem**

- ***Closed-loop control system*: Sistem yang mengukur isyarat keluaran sebenar dan membandingkannya dengan isyarat yang dikehendaki.**

- ***Regulating control system*: Sistem kawalan suapbalik yang isyarat masukannya tetap atau berubah perlahan.**

- ***Tracking control system*: Sistem kawalan yang isyarat masukannya berubah secara pantas.**

- ***Servomechanism*: Sistem kawalan suapbalik yang keluarannya berbentuk mekanikal seperti kedudukan, kelajuan dan pecutan.**

- ***Negative feedback*: Isyarat keluaran yang disuapbalik supaya ia dibandingkan dengan isyarat masukan**

- ***Positive feedback*: Isyarat keluaran yang disuapbalik dan dicampurkan dengan isyarat masukan**