XMUT315 Control Systems Engineering

Note 1: Control Systems and Engineering

A. Introduction to Control System

The control systems are designed to manage and regulate the behaviour of devices or systems.

1. Why we study control system and engineering?

Control system and engineering focus on the analysis and design of systems to improve the speed of response, accuracy, and stability of the system.

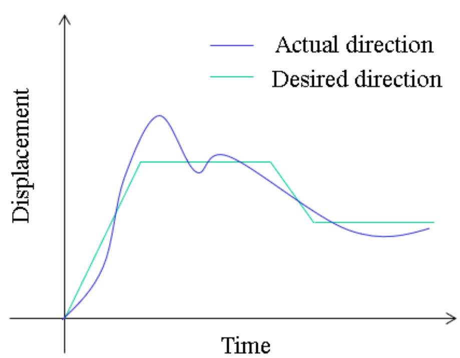


Figure 1: Use of control system

A control system is needed to manage and regulate the behaviour of devices or system. Using the example given in figures above, attempt to plot:

- Input distance to car system from car going up curb (a step) over time.
- Output distance of driver at the same time.

Notice that control system is needed to avoid unwanted outcome of the operation of the system e.g. the illustrated car crash.

1.1. Why do we use control?

Using control system engineering, we could achieve the aims of the system efficiently and effectively. The list given below is not an exhaustive goal of the system:

- Track reference – operating the system under control.
- Speed of response – operating the system within the limit of desired operation.
- Avoid overshoots – preventing the system to veer off from specification and errors.
- Avoid steady-state errors – reaching the goal of the system without deviation.

Figure 2: Goal of control system

- Autonomous operation – operating without any direct interaction or supervision.
- Avoid disturbances – steer clear from the obstacles along the way.
- Understand natural systems – to know better relevant systems outside the system and the environment where system is located.

1.2. What is a System?

Systems are built of signals (variables), constants, and differential operators. For complex systems, we might see that systems are often built of sub-systems (e.g. smaller and/or less complex systems).

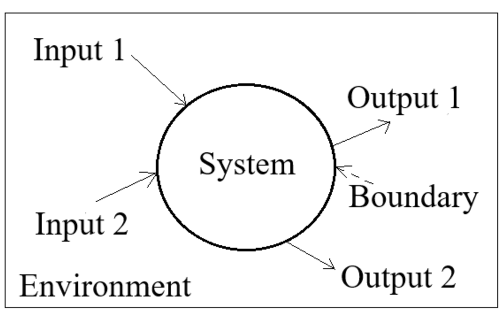


Figure 3: A system and its typical components

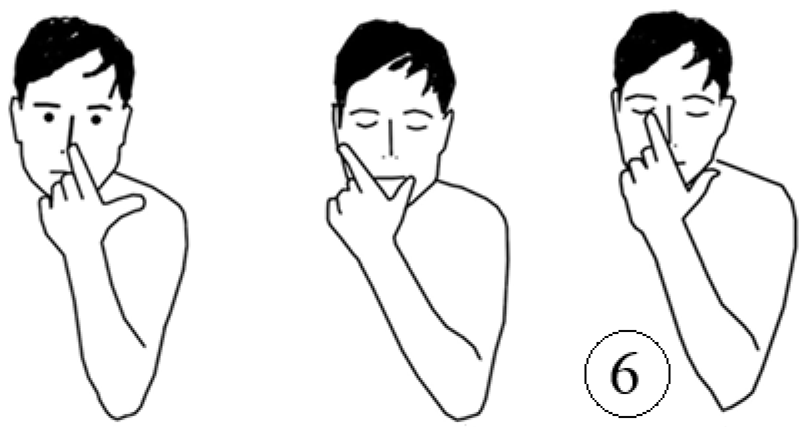
As shown in the figure above, system exists in an environment, and it receives input and produce output. There is also a boundary that borders between the system and the environment.

1.3. Are Systems Perfect?

Consider the following examples of human perception systems as shown in the figure below under different conditions:

Case 1: Open eyes (e.g. a system with feedback):

- Extend your arms out at shoulder height
- Touch the tips of your little fingers in front of your nose!



Case 1 Case 2 Case 3

Figure 4: Example illustration of a system under different conditions

Case 2: Close eyes (e.g. a system without feedback):

- Extend your arms out at shoulder height
- Touch the tips of your little fingers in front of your nose.

Case 3: Strangeness (e.g. a system with disturbances):

- Make a circle with your right foot going in the clockwise position.
- While you are doing that, draw a six with your right hand.

Notice that when the system was without feedback, it was very hard to be able to perform the task given compared when it was with feedback mechanism implemented within the system.

Also, the disturbances that introduced to the system made the system to deviate from its intended operation. It is also possible that we observe a different characteristic and response of the system because of the disturbances.

1.4. Feedback

Feedback is a mechanism where the output signal is given back to the input signal as illustrated in the figure below.

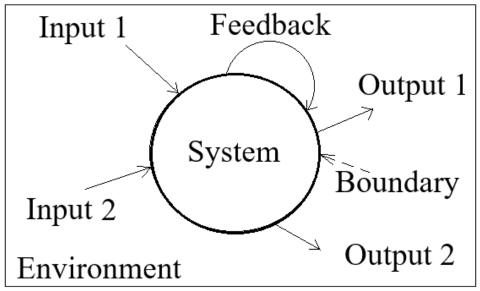


Figure 5: Input, output and system of a feedback mechanism

Feedback is typically employed in the system to provide some sorts of evaluative and corrective data or information about an action, event, or process to the original or controlling source.

1.5. Open vs. Closed Loop

Open loop indicates that the system is operated without feedback where closed loop is operated with feedback. There are differences between open and closed loop system.

1. Open loop: it is simple to implement but does not know the actual value of the control variable so is vulnerable to changing the conditions.
2. Closed loop: it accounts for changes in conditions, but at the expense of increased complexity and can become unstable if care is not taken in its design.

Note: Closed loop control is sometimes called feedback control.

Questions:

1. Explain the advantages and disadvantages of open loop control.
2. Explain the advantages and disadvantages of closed loop control.

1.6. Engineering Systems

An engineering system is a set of components connected to accomplish a useful task. In each engineering systems, there are a combination of components that work in synergy to collectively perform a useful function. The focus of engineering system is to design, integrate, and manage complex systems over their life cycles.

For given complex systems, we often employ modelling to simplify the analysis and design of the system. Complex systems require extensive derivation effort from first principles compared with modelling of the system.

When building up a model system, there are number of principles that we need to consider:

- Components should be easily identifiable.
- Components should have a simple and clearly defined interaction with other components.
- Components numbers should be minimised.

1.7. Laplace Operator '*s*'

In derivation of the system equation, Laplace transform is useful for eliminating the mathematical differentiation and integration and it replaces the derivation with simple algebra processes.

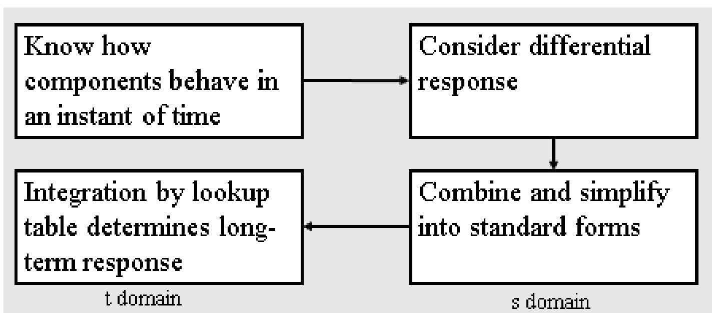


Figure 6: Modelling processes

The transformation process given in the figure below is how Laplace transform is used in the modelling process given in the figure above.

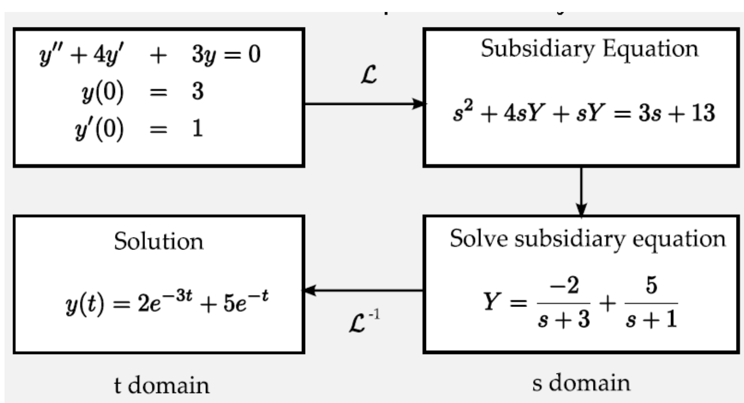


Figure 7: Laplace transform processes

1.8. Systems Analysis

System analysis is initiated to enable us to understand better the characteristics and behaviour of the system. Typically, analysis is performed before the design effort, especially for systems that are non-standard or not well understood. To analyse a system:

- We identify an input signal [a variable].
- Using block diagram components [basic block, summing junction, and take-off point].
- We combine internal signals [modified variables].
- To produce the output signal [another variable].
- The Input-Output relationship may then be determined.

2. Dynamic Systems

As an introduction, consider dynamic systems where these change with time. As an example, consider water system with two tanks as shown in the figure below:

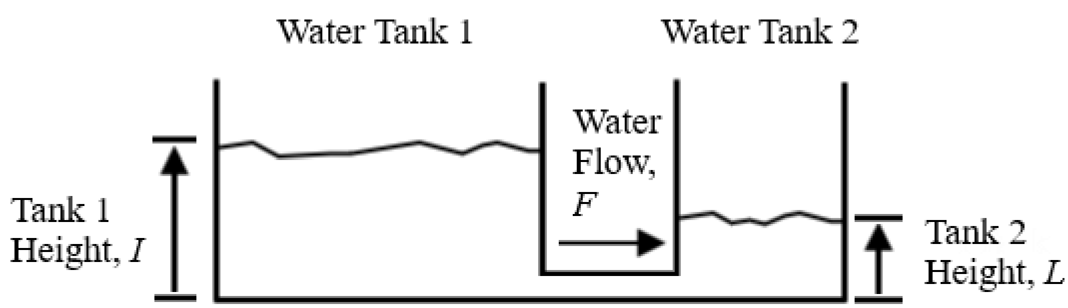


Figure 8: Tank dynamic system

As illustrated in the figure, water will flow from first tank to second tank. When will it stop following? The water stops when levels equal e.g. height of water in the smaller tank is the same as the water in the bigger tank. Why stop then? Why flow at all? Should we plot the time response of the system? We need to analyse the given system to understand its characteristics and behaviour.

2.1. Dynamic Flow

When we consider the given two-tank system example, we observe that the level change is not instantaneous initially.

We know that a large height difference will result on a large flow, hence the height of the water in the smaller tank (L) is up a lot.

Then, when the height difference less, this leads to less flow and the height of the water in the smaller tank (L) increases, but by less.

Later, the height difference 'lesser'. This results in less flow and the height of the water in the smaller tank (L) up, but by less, etc.

Graphically the variation of level L and flow F is as shown in the figure below. The height of the water is initially increasing very rapidly, and flow of the water is high, but as the height difference between the two tanks is getting smaller, the rates of height increase, and flow decrease are slowing down.

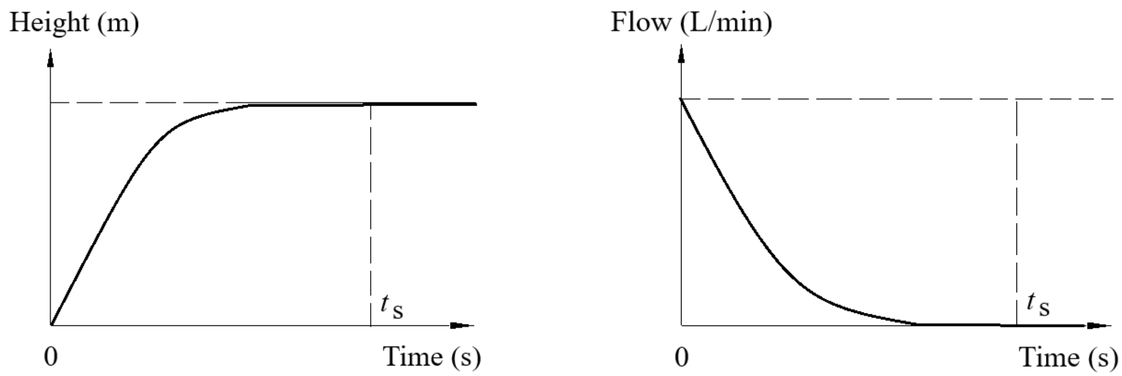


Figure 9: Graphs of level and flow vs. time in the tank system

2.2. Time Response

We have dynamic equation for L in terms of I. We need to put into 's' domain to get output over input function (e.g. application of Laplace transform). Then, we add a unit step input for I. We integrate to determine variation of L. As t gets larger, exponential term disappears. Finally, L tends to input.

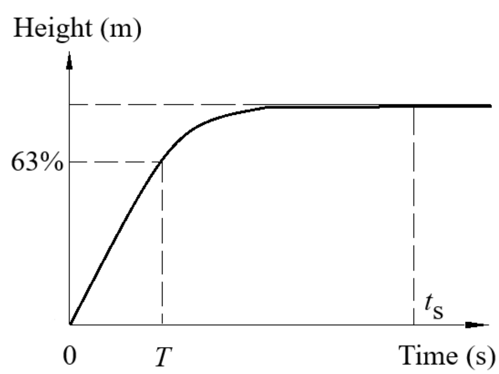


Figure 10: Time response of the tank system

As illustrated in the figure above, the time response of the tank system is derived as follows. We have a dynamic equation that represents the given two-tank system:

$$\frac{dL}{dt} = \frac{I - L}{CR}$$

Put into 's' domain and rearrange:

$$sL = \frac{I - L}{CR} \qquad \text{and} \qquad \frac{L}{I} = \frac{1}{1 + CRs}$$

Add a unit step input for I:

$$L = \frac{1}{s}\left(\frac{1}{1 + CRs}\right)$$

Integrate to determine variation of L:

$$L = 1 - e^{-\frac{t}{T}}$$

As t gets larger, exponential term disappears. L tends to input I.

3. Car Suspension Model

For a mechanical system of a car suspension system as shown in the figure below, explain what happens when a car goes over a bump?

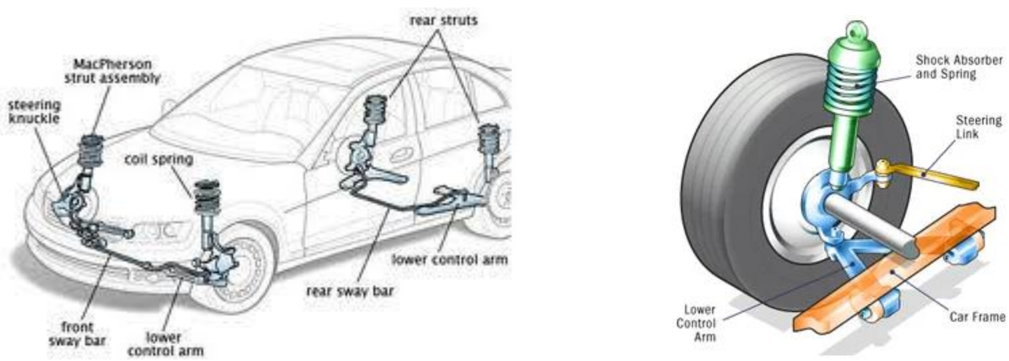


Figure 11: Car suspension system

For explaining what happens when a car goes over a bump, simplify to single-input-single-output system. First, we form individual component models. Then, we determine their relationships (use physical laws). We combine (and simplify if possible) one part with another. This gives us an instantaneous differential equation, but we want a time response. So, the next step in our analysis is to analyse the time response based on this differential equation.

3.1. Standard Mechanical Systems Model

There are several standard modelling components of mechanical system e.g. spring (S), damper (D), and mass (M). Furthermore, in the model, forces acting in spring ($F = kx$), damper ($F = bdx/dt$), and mass ($F = md^2x/dt^2$) where: k = spring constant, b = damper constant, x = displacement, and m = mass.

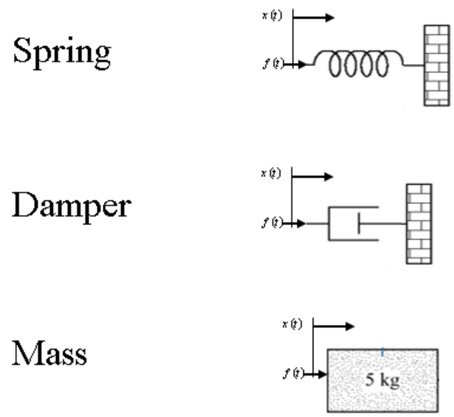


Figure 12: Standard parts in the mechanical system model

As shown in the figure above, a simple mechanical system can be represented as a system that is made up of spring, damper and mass.

3.2. Mechanical System Model of Car Suspension

The car suspension system is a physical system that can be represented with mechanical system model e.g. a model consisted of standard mechanical system as given in the previous section. Since in practice car suspension system is a complex system, this often involves simplification of components of the system.

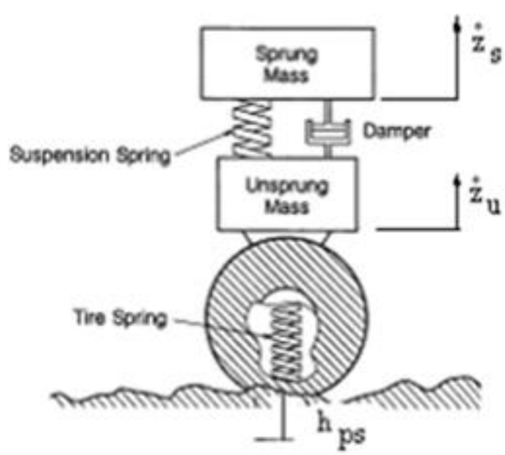


Figure 13: Mechanical system model of a car suspension system

As illustrated in the figure above, the practical car suspension system is modelled as a system that has spring (k), damper (c) and mass (m).

3.3. Block Diagram

From the simplified mechanical system model of car suspension system, applying Newton second law of motion, we could then derive its differential equation.

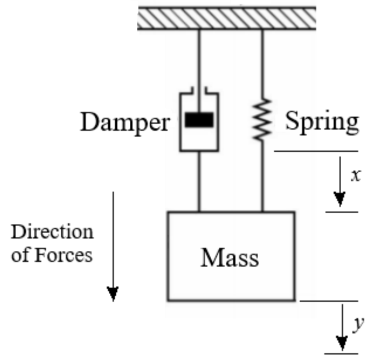


Figure 14: Simplified car suspension system (y = applied force and x = displacement)

When the system is at equilibrium, the Newton's law says:

$$\sum f(t) = 0$$

For a given car suspension system:

$$F_{mass}(t) + F_{spring}(t) + F_{damper}(t) = 0$$

Where:

$$F_{mass}(t) = m\left(\frac{d^2y(t)}{dt^2}\right); \qquad F_{spring}(t) = k\big(x(t) - y(t)\big); \qquad F_{damper}(t) = b\left(\frac{dx(t)}{dt} - \frac{dy(t)}{dt}\right)$$

Note: y is distance due to applied force and x is displacement.

Then, derive the differential equation for the system:

$$m\left(\frac{d^2y(t)}{dt^2}\right) + b\left(\frac{dy(t)}{dt}\right) + ky(t) = kx(t) + b\left(\frac{dx(t)}{dt}\right)$$

Applying Laplace transform, derive the transfer-function equation of the system:

$$H(s) = \frac{dy(s)}{dx(s)} = \frac{k + bs}{Ms^2 + bs + k}$$

Represent the model in the block diagram:

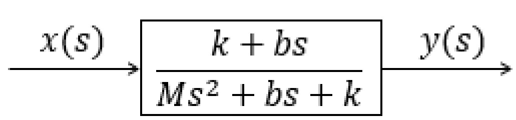


Figure 15: Block diagram model of simplified car suspension system

Determine the block diagram for the following electrical system? Use standard modelling components of electrical system e.g. inductor (L), capacitor (C) and resistor (R). Analyse the behaviour of the circuit.

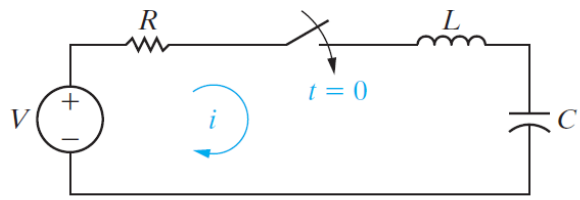


Figure 16: Series RLC circuit

The system is a second-order electrical system with a transfer function:

$$\frac{V_C(s)}{V(s)} = \frac{1}{LCs^2 + RCs + 1}$$

3.4. Examples of Control Systems

There are many examples of control systems. As shown below, we see a self-configured and adjustment robotic set up in the automatic manufacturing system. Goods to be manufactured are assembled in the production line in a factory using robots and automatic systems.

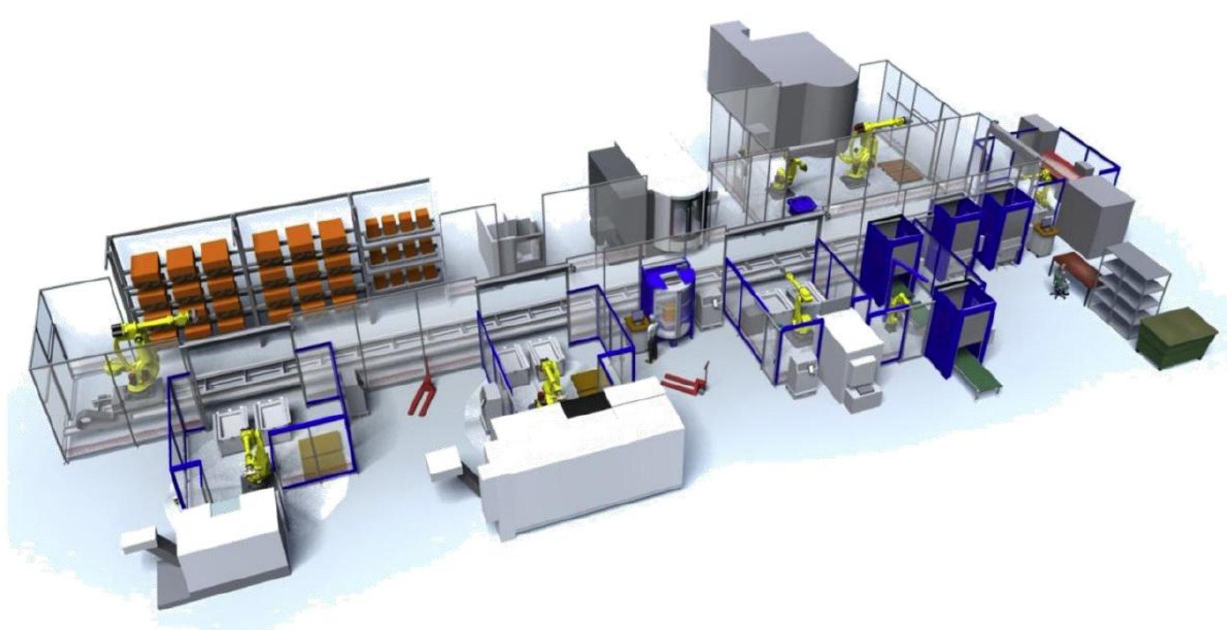


Figure 17: Automatic assembly line in a factory

Autonomous navigation of the vehicle or transportation system is another example of control as shown below. The car can navigate the road without any human interferences.

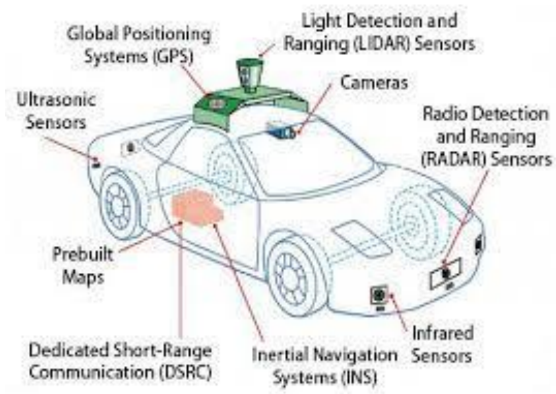


Figure 18: Autonomous navigation vehicle

As shown in the figure below, we can also see an example of control system in form of a control and management of the networked renewable energy resources. Energy in the system is managed through various components of the system.

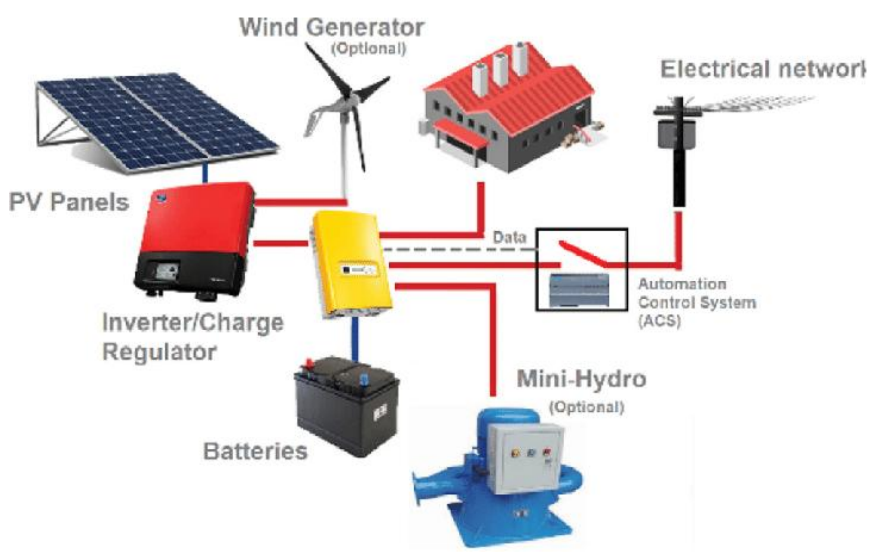
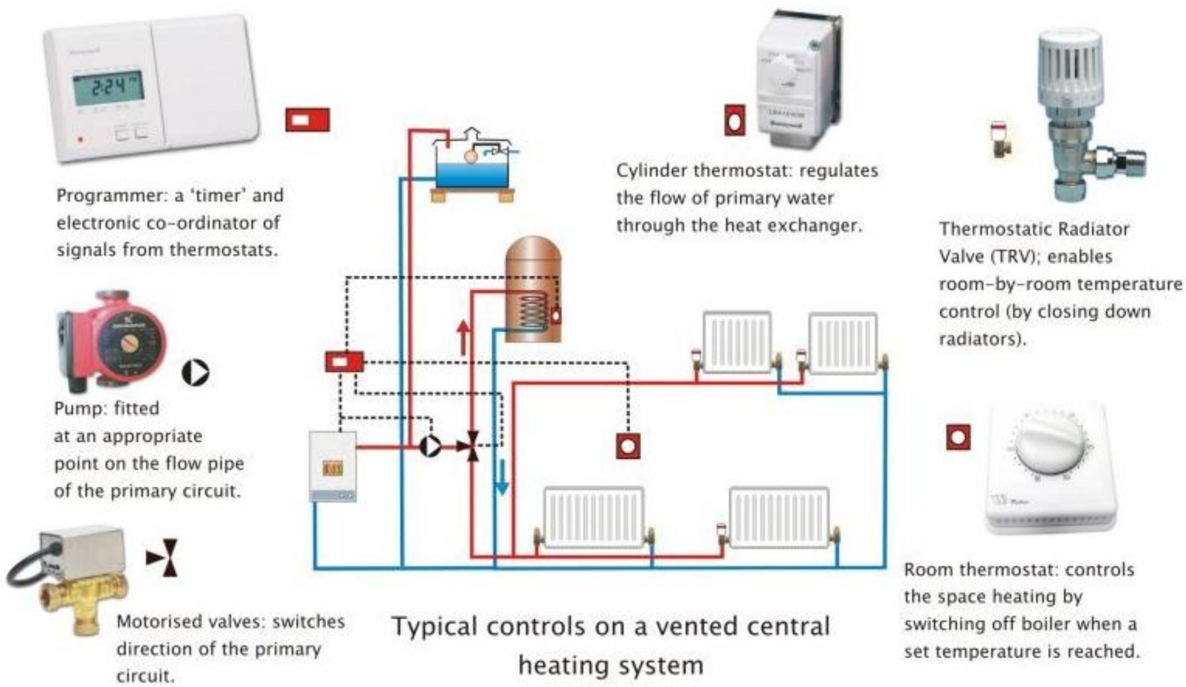


Figure 19: Renewable energy system

Example for Tutorial 1 – Example of Control System

A vented central heating system operates by sensing the difference between the thermostat setting and the actual temperature and then opening a fuel valve an amount proportional to this difference.



a. Describe the fundamental concept and principle behind a typical temperature control system. [2 marks]

b. Draw a functional closed-loop block diagram identifying the input and output transducers, the controller, and the plant. [5 marks]

c. Further, identify and describe briefly the input and output signals of all subsystems previously described. [3 marks]

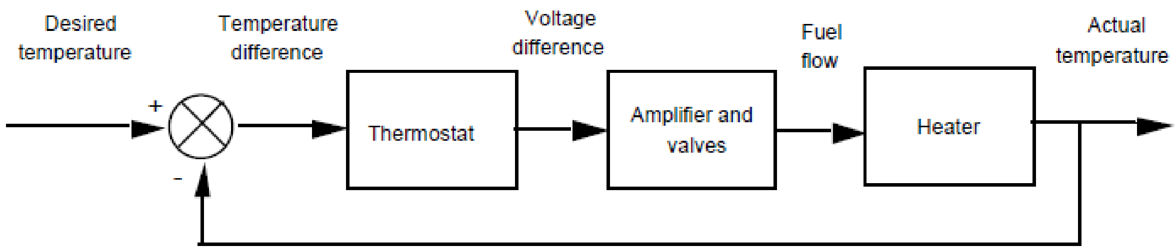
Answer

a. The concept behind the temperature control system is a feedback control system in which the temperature in each room is maintained to be constant at desired temperature.

The actual temperature is picked up by temperature sensor and compared with the desired temperature.

Depending on the difference between the actual with the desired temperature, the feedback mechanism provides the ability for the system to adjust the setup of the heater, hence increasing or decreasing the temperature.

b. The functional closed-loop block diagram of the temperature control system is as shown in the figure below



c. The input and output signals of all subsystems are:

Thermostat Subsystem:

- Input – Temperature difference (e.g. actual temperature – desired temperature).
- Output – Voltage difference (e.g. due to temperature difference that is converted to voltage by the thermostat)

Amplifier and Valves Subsystem:

- Input – Voltage difference.
- Output - Fuel flow (i.e. amount of fuel to power the heater).

Heater Subsystem:

- Input – Fuel flow.
- Output – Actual temperature (e.g. sensed by the thermal sensor in the heater).

B. Introduction to Control System Engineering

Control engineering or control systems engineering is an engineering discipline that deals with control systems, applying control theory to design equipment and systems with desired behaviours in control environments.

4. Classical Control

Classical control was developed in the 1930's (H. W. Bode and H. Nyquist) and 1940's (W. R. Evans). It allows effective control system design without use of computers.

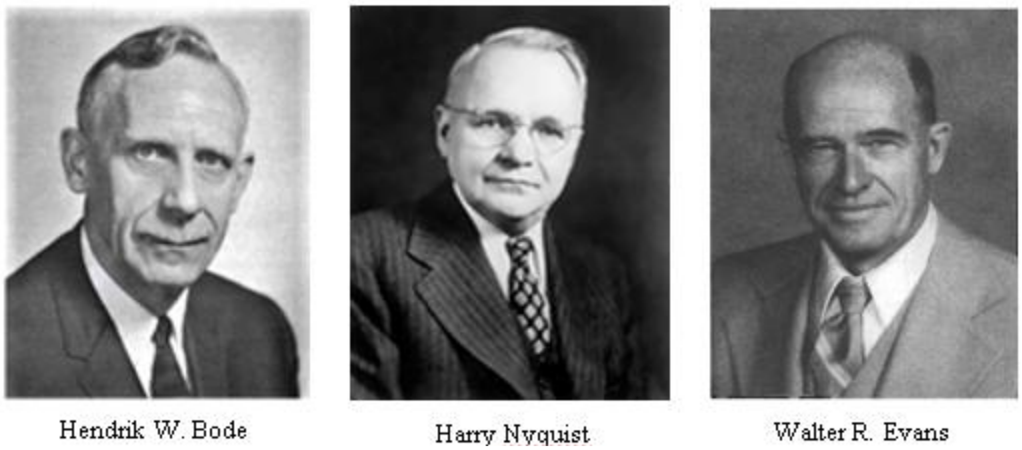


Figure 17: Inventors in classical control

Classical control is most useful for systems:

- Linear Time Invariant (LTI).
- Single Input, Single Output (SISO).

For other systems, use multivariable control systems or nonlinear control systems.

Subsequent ECEN415 Advanced Control Engineering at VUW covers these other systems, digital control systems, and applications of further control system techniques.

We will also continue to consider only continuous time systems, though these tools can all be used in discrete time. The various techniques in control system engineering provide insight into the system's behaviour. These techniques typically do not yield a single "correct" compensator design, and they require a level of engineering judgement.

4.1. Topics in Classical Control

In addition to the various technical techniques that need to be learned, there is some general classical knowledge and skills in control systems:

- Transformation skills – from actual practical system or entity to physical model, from time domain to frequency domain, etc.
- Performance identifications and analysis – observe and measure characteristics and behavior of the system.
- Stability analysis – evaluate stability of the system.
- Block diagram – apply model for simplifying the analysis and design of the system, especially complex system.
- Other relevant techniques and tools in control system engineering.

4.2. Knowledge and skills in the course

More specifically, knowledge and skills that will be covered in the course e.g. techniques and tools in control system engineering:

- Modelling from physical systems.
- Feedback control systems.
- Transient and steady-state response analysis.
- Time domain analysis.
- Frequency response analysis.
- Compensation design.

5. Feedback Control Systems

Feedback is required in systems that are aware about their conditions and for any that can manage its characteristics and performance.

5.1. Feedback Control Systems

For a (closed loop) feedback control system as shown in the block diagram given in the figure below, the output from feedback pathway is compared with the input. The comparison results in error signal that is fed into the plant to become output.

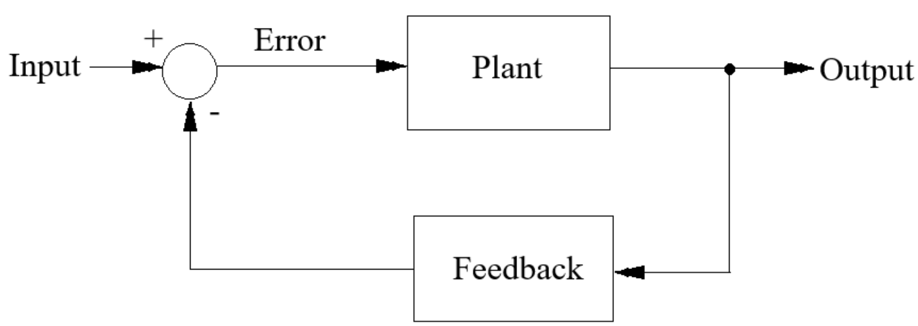


Figure 18: Feedback control system

Notations:

- Feedback = Output
- Error = Input - Feedback
- Output = Error x Plant

Advantages of feedback:

- Plant more responsive to changes in input.
- Eliminate noise.

Disadvantages of feedback:

- Added cost and complexities to implement.
- Could lead to issues in performance and stability.

5.2. System Topology and Notation

Closed-loop feedback system is used for analysing the performance and stability of the control systems. Analysis and design of complex control systems is performed on block diagrams for simplification. Then, design of compensation mechanism is intended to improve the performance and stability of a given system/plant. The compensation depends on the types and applications of controller/compensator.

6. Graphical Techniques - A Preview

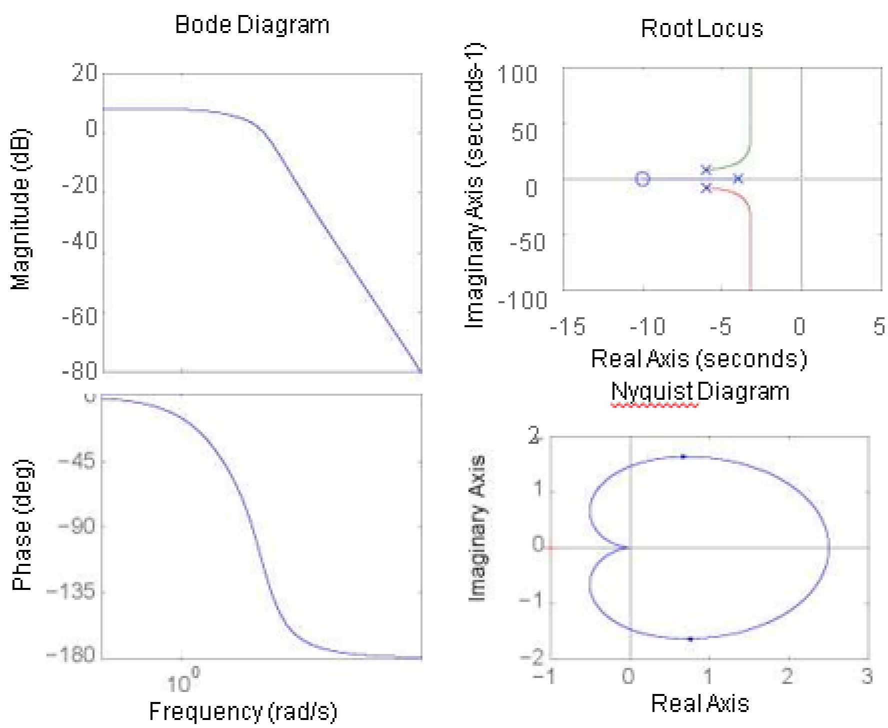


Figure 19: Graphical techniques in classical control engineering

The figure above shows several graphical techniques in classical control engineering e.g. frequency response (Bode) plots, root locus diagram, and Nyquist plot.

6.1. Bode Plots

The frequency response plot, or colloquially called Bode plot after its inventor, consisted of magnitude and phase plots. It is used to analysis and design system based on its frequency response.

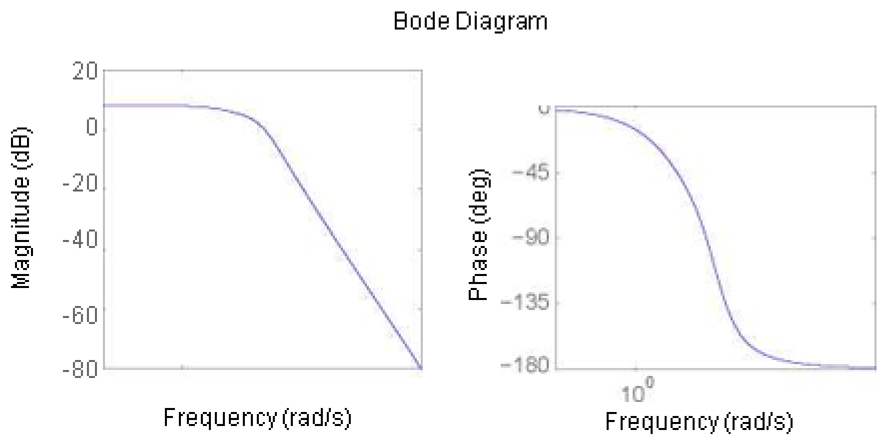


Figure 20: Bode plots diagram

6.2. Root Locus Diagram

Root locus diagram is a graph constructed based on the transfer function (output/ input) of the system. This diagram is typically used for analysis and design of system performance and stability.

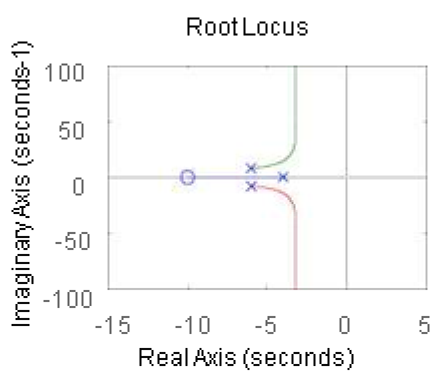


Figure 21: Root locus diagram

6.3. Nyquist Plot

The Nyquist plot is created based on polar plots of system response. It is used for further analysis and design of system stability. Another variant of this plot is a Nichols plot that is a plot of gain vs. phase shift of the system. It is also used for analysis and design of system stability.

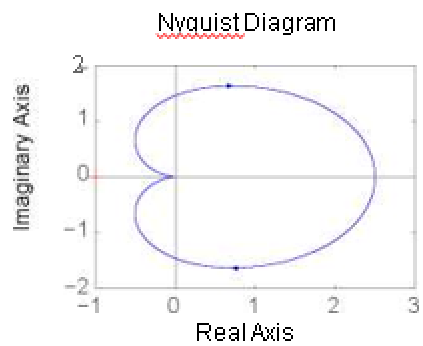


Figure 22: Nyquist diagram

7. Compensator Design

For systems with issue and problem, we need application of compensator to fix them. We will generally implement the compensator in the feedback path, but it could be placed in the forward path. The compensator works to improve the performance of the control system. Most common placement of compensator is in feedback path as shown in the figure below. Less hardware and software are required for this scheme.

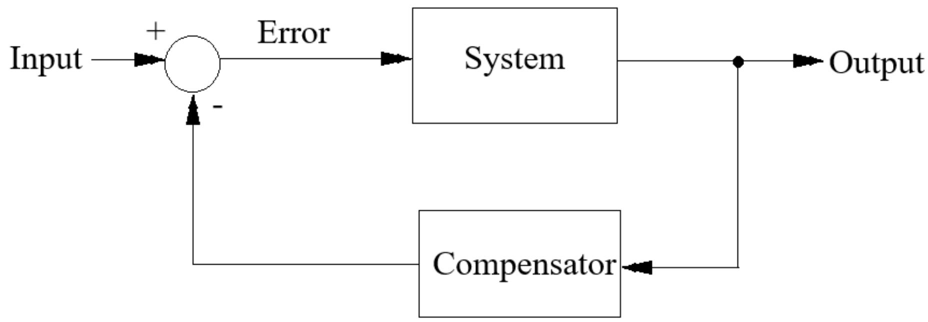


Figure 23: Compensator in the control system

The compensator is designed to match overall behaviour of the control systems to design requirement. We will focus on modifying system characteristics by applying feedback. We will be able to tailor the closed loop transfer function with the addition of a compensator.

The design of the compensator is a compromise between two competing goals.

- Performance: Keeping the open loop gain high reduces system errors and the effects of disturbances.
- Stability: The closed loop system must be kept stable by carefully managing the gain where the phase approaches -180°.

The design of compensators can often be philosophically reduced to two (inter-related) problems:

- One operating at low frequencies to achieve the required performance.
- The other at high frequency to ensure stability.

There are varieties of approaches to designing a compensator.

1. Choose a compensator's structure and then tune manually.
2. Choose a compensator model and tune using a "recipe" (e.g. Ziegler-Nichols).
3. Use a model and solve it for desired pole locations.
4. Measure the system performance and use a graphical technique.
5. Use a mathematical model with a graphical technique.
6. Use mathematical tools to achieve optimal performance (see ECEN415 - Advanced Control Engineering).

In the remaining lectures, we will concentrate on the collection of graphical methods that form the heart of classical control (items 4 and 5 in the list):

- Measure the system performance and use a graphical technique.
- Use a mathematical model with a graphical technique.

Example for Tutorial 2 – Example of Control System Engineering Application

A Segway Human Transporter (HT) as shown in the figure below is a two-wheeled vehicle in which the human operator stands vertically on a platform.

- As the driver leans left, right, forward, or backward, a set of sensitive gyroscopic sensors sense the desired input.
- These signals are fed to a computer that amplifies them and commands motors to propel the vehicle in the desired direction.
- One very important feature of the HT is its safety: The system will maintain its vertical position within a specified angle despite road disturbances, such as up hills and downhills or even if the operator over-leans in any direction.

Figure 1: The Segway's Human Transporter (HT) (http://segway.com)

a. Describe the functionalities of gyroscope that works behind the human transporter. [2 marks]

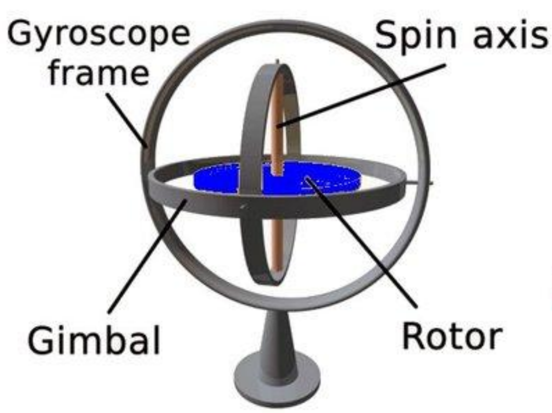
b. A conventional gyroscope would be cumbersome and difficult to maintain practically, describe how Segway's engineers invent the same effect with a more practical mechanism. [2 marks]

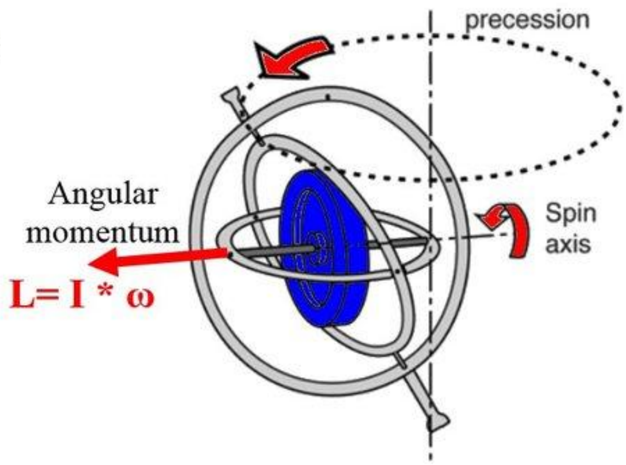
c. Draw a functional block diagram of the system that keeps the system in a vertical position. [4 marks]

d. Indicate and describe briefly the input and output signals, intermediate signals, and main subsystems. [6 marks]

Answer

a. Human transporter is based on a device called gyroscope having a spinning disc or wheel mechanism that harnesses the principle of conservation of angular momentum e.g. the tendency for the spin of a system to remain constant unless subjected to external torque.





There is also feedback control system employed in the human transporter to maintain a steady position.

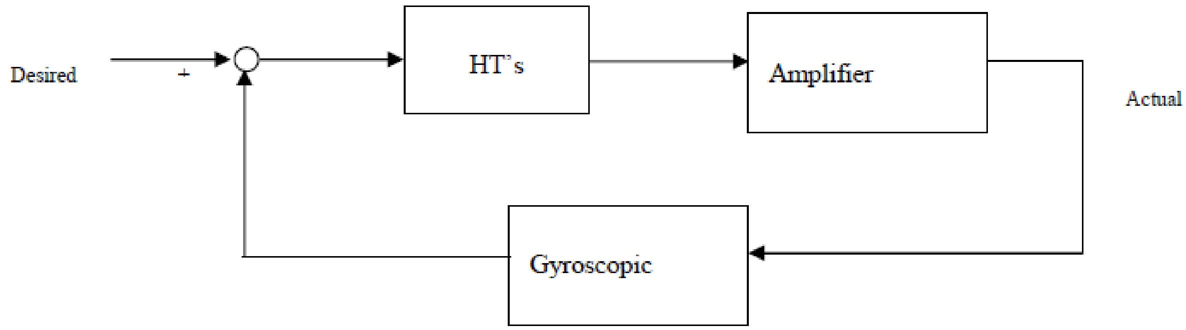
b. For the gyroscope, the engineers at the Segways use a special solid–state angular rate sensor constructed using Silicon. This sort of gyroscope determines an object's rotation using the Coriolis effect on a very small scale.

Note: the Coriolis effect is the apparent turning of an object moving in relation to another rotating object. For example, an airplane traveling in a straight line appears to turn because the Earth is rotating underneath it.

A typical solid-state silicon gyroscope consists of a tiny silicon plate mounted on a support frame. The silicon particles are moved by an electrostatic current applied across the plate. The particles move in a particular way, which causes the plate to vibrate in a predictable manner.

But, when the plate is rotated around its axis (that is, when the Segway rotates in that plane), the particles suddenly shift in relation to the plate. This alters the vibration, and the change is in proportion to the degree of rotation. The gyroscope system measures the change in vibration and passes this information on to the computer. In this way, the computer can figure out when the Segway is rotating along particular axes.

c. The functional block diagram of the human transporter is as shown in the figure below.



d. The input and output signals, intermediate signals and main subsystems are:

Human Transporter (HT) Subsystem:

Input – Position difference (Actual – Desired).

Output – Voltage difference.

Amplifier Subsystem:

Input – Voltage difference.

Output – Power (e.g. motor and actuator).

Gyroscopic Subsystem:

Input – Power.

Output – Actual position.