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Embedded Systems and Industrial Controller EE5563 (1)

Reading List

- Online Lecture Material at (www.brunel.ac.uk/~emstaam)
- **C. W. De Silva, Modelling and Control of Engineering Systems, CRC Press, Francis & Taylor, 2009.**
- **M. P. Groover, Automation, Production Systems, and Computer Integrated Manufacturing, 3rd Edition, Pearson International, 2007.**
- **Mechatronics: electronic control systems in mechanical and electrical engineering, W. Bolton, 4th Edition, Pearson Education Ltd, 2008.**

The aim of this module is to introduce students to the **concepts**, **principles**, **infrastructure**, **technologies**, and **implementation** of embedded and industrial control systems.

Aim

Objectives

1. Gain knowledge and understanding of the fundamentals of modelling and control of engineering systems.
2. Utilise the principles of control system in design, implementation and test of systems instructions on artefacts
3. Insight to sensors, actuators I/O devices and digital systems
4. Critically evaluate and compare various control methods for implementation on artifact design as well as strategies for monitoring and automation of systems.
5. Implementation and installation of electronic controls on electromechanical artefacts.
6. Utilise the knowledge and skills acquired in the theoretical part of the module to design and implement or interpret various automation configurations in the Automation and Control Laboratory.

Methods

- Lectures on Theory (40% on the module content)
- Practical Laboratory Exercises (60% of the module content)

1. Assignment (artefact) embedded systems including demonstrator and 1500 word report.

   Submission Deadline: 14/02/14

2. Assignment (sensors, actuators and systems monitoring), demonstrator and 1500 word report

   Submission Deadline: 14/03/14

3. Assignment (Industrial Automation, Programmable Logic Controllers, Industrial network) demonstrator and 2000 word report on the final project

   Submission Deadline: 21/04/14

Assessment

Indicative Content

- **Modelling and Control of Engineering Systems**
  - Principles of control engineering,
  - Application areas,
  - Dynamic systems,
  - Linearisation, and
  - Transfer Functions
- **Sensors, Actuators and Microcontrollers**
  - Analog-to-digital conversion,
  - digital-to-analog conversion, and
  - I/O devices for discrete data

Indicative Content Cont.

Industrial Monitoring and Control Systems

- Enabling suite of technologies for research and industrial applications for example (National Instruments suite of technologies for system monitoring and control), and
- Introduction to industrial controllers such as Programmable Logic Controllers, Industrial networks (i.e. Ethernet, Control Net, OPC) emulating a real plant scenarios.

Applied Industrial Control and Automation

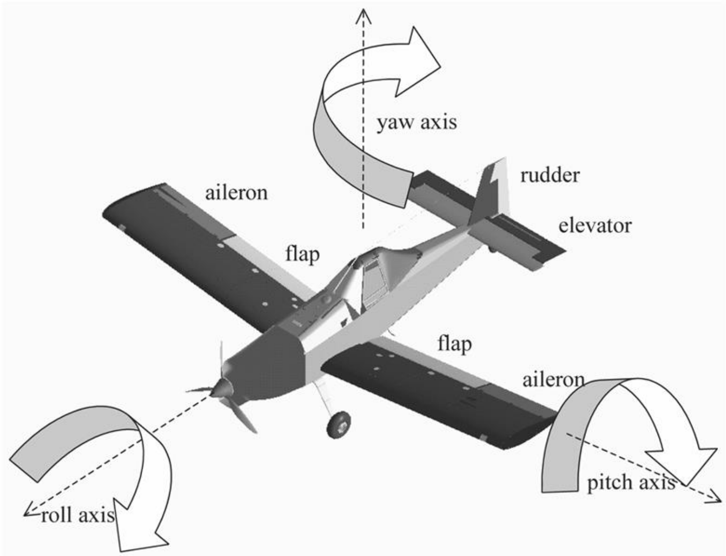
- Embedded system,
- Industrial networks set-up,
- systems logics, and
- systems integration

In this Module

1. Modelling and Evaluation of Control Systems: Use of simulation software tools to estimate the **accuracy**, **responsiveness**, **stable**, **noise handling, sufficiently sensitive to input signals**.

2. Application of Control principals in the real world: Use sensors, actuators, controller, communication network to meet the functional and processing specifications (Artefact or Plant)

The emphasis will be on the latter


yaw axis
aileron
rudder
elevator
flap
flap
aileron
pitch axis
roll axis

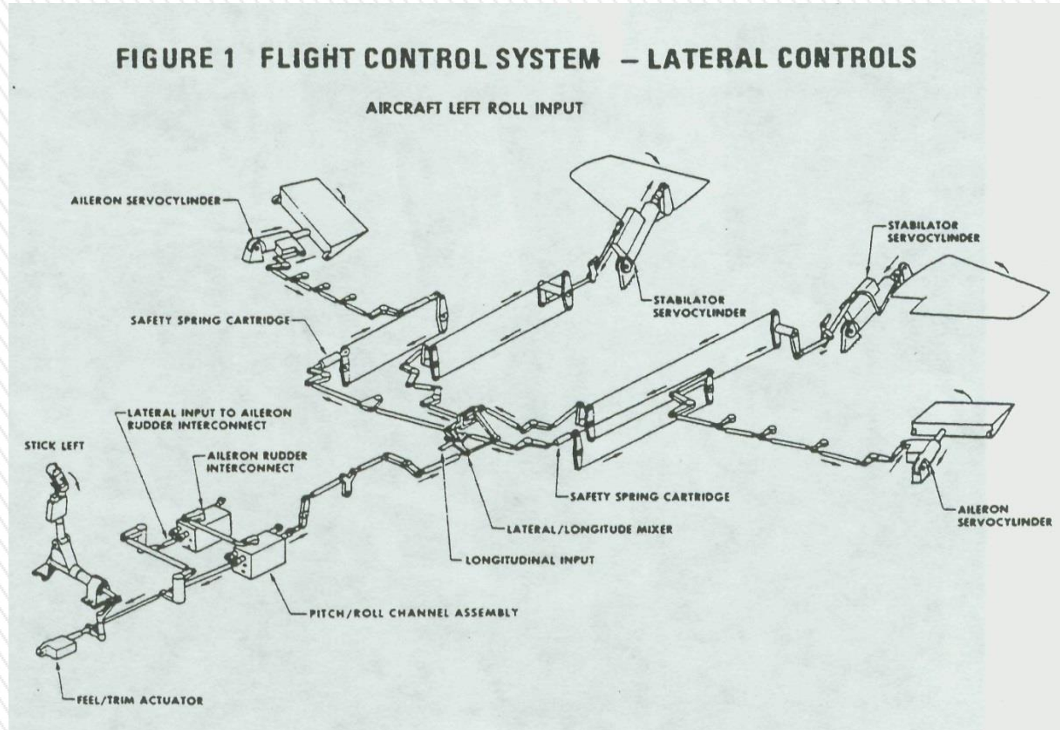
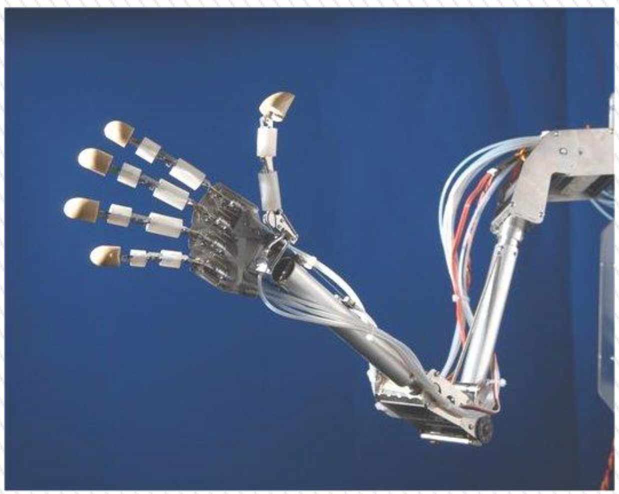
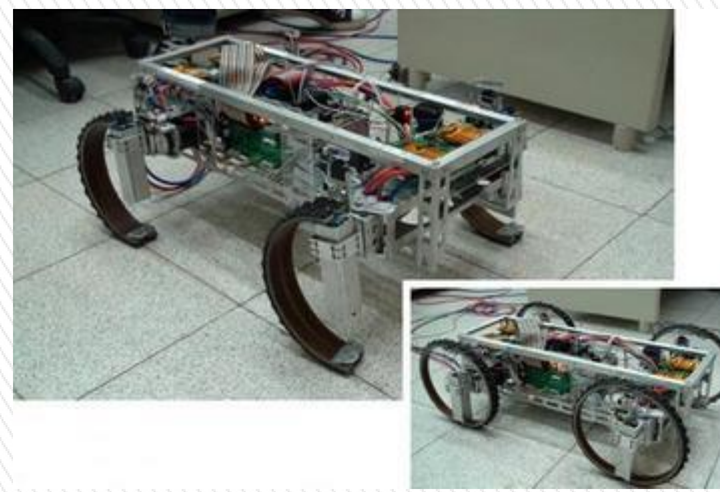
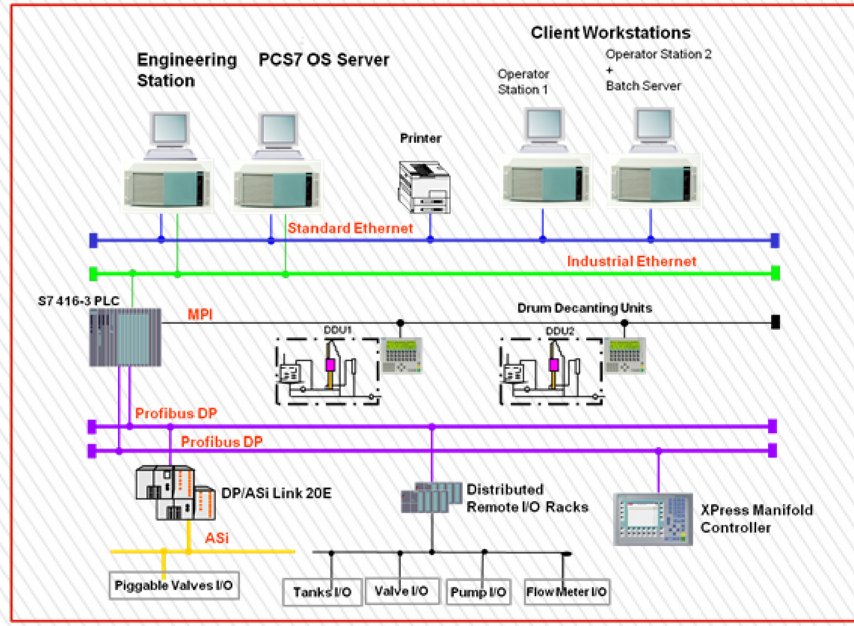


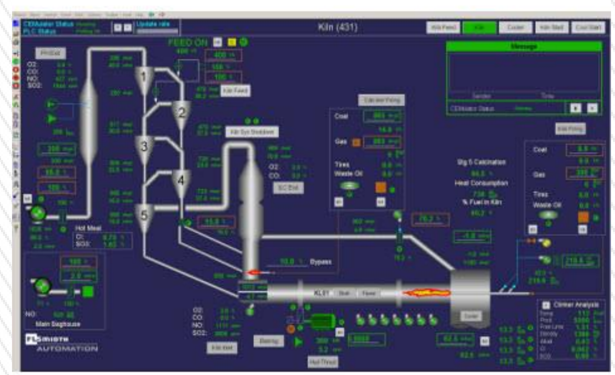
FIGURE 1 FLIGHT CONTROL SYSTEM – LATERAL CONTROLS
AIRCRAFT LEFT ROLL INPUT
AILERON SERVOCYLINDER
STABILATOR SERVOCYLINDER
STABILATOR SERVOCYLINDER
SAFETY SPRING CARTRIDGE
LATERAL INPUT TO AILERON RUDDER INTERCONNECT
STICK LEFT
AILERON RUDDER INTERCONNECT
SAFETY SPRING CARTRIDGE
AILERON SERVOCYLINDER
LATERAL/LONGITUDE MIXER
LONGITUDINAL INPUT
PITCH/ROLL CHANNEL ASSEMBLY
FEEL/TRIM ACTUATOR



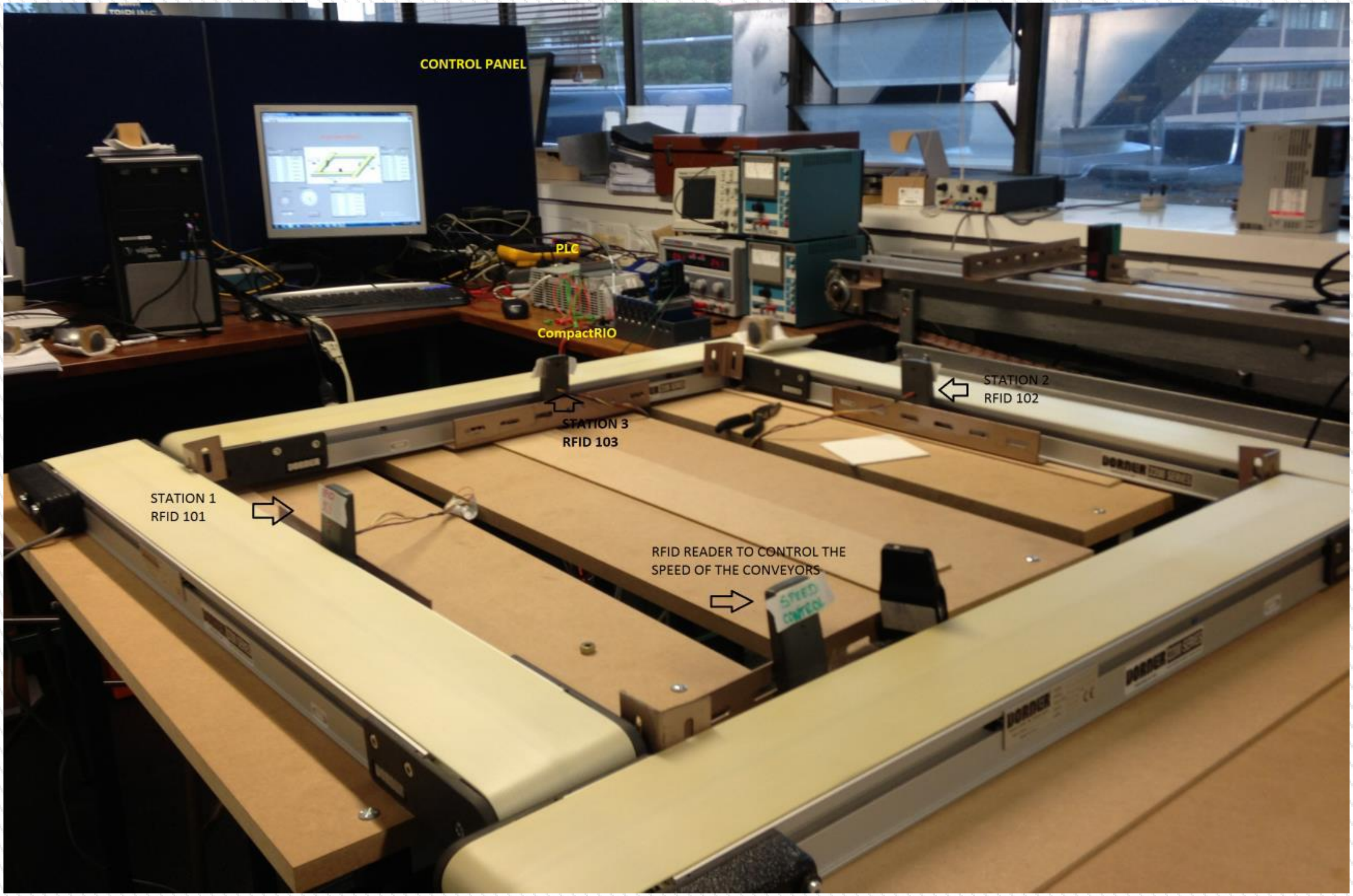


Artefacts


Client Workstations
Engineering Station
PCS7 OS Server
Operator Station 1
Operator Station 2
+
Batch Server
Printer
Standard Ethernet
Industrial Ethernet
S7 416-3 PLC
MPI
Drum Decanting Units
DDU1
DDU2
Profibus DP
Profibus DP
DP/ASi Link 20E
Distributed
Remote I/O Racks
XPress Manifold
Controller
ASi
Piggable Valves I/O
Tanks I/O
Valve I/O
Pump I/O
Flow Meter I/O



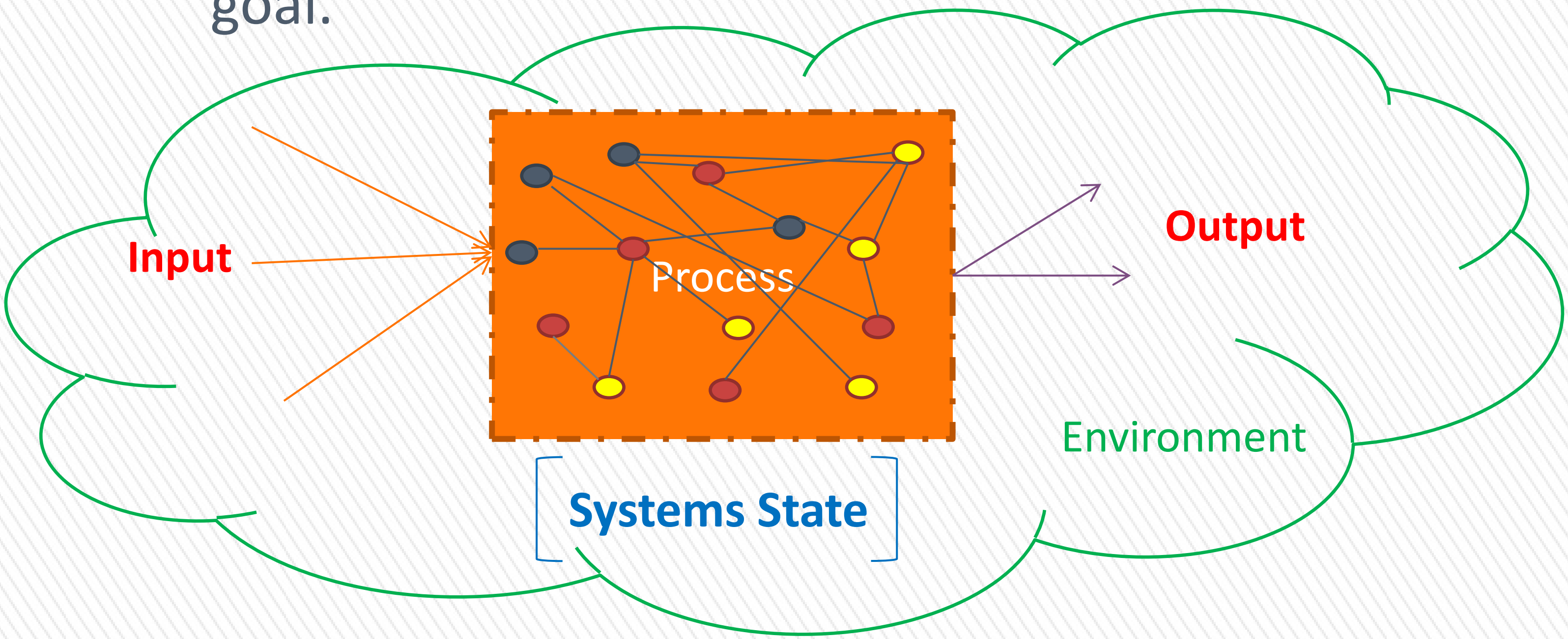
Plants



SERG Laboratory

» **System:**

A set of interacting components that seek a common goal.



The state (behaviour) of the system is often described by a variable or by a series of variables

System

» **Control:**

The process of causing the variables of a system to conform to a desired value.

» **Controller:**

The purpose of a controller is to make a system behave in a desired manner.

» **Control Engineering:**

Design and development of the tools and techniques to measure system parameters and ensure that they conform to the required specifications.

Control

» Automation and Robotics
» Transport Systems
» Distribution Systems (Power and Water)
» Mechatronics
» Manufacturing
» Medical Devices
» Aerospace
» Defence and many more

Applications

Main Reasons

Control systems are built for 4 main reasons:

» power amplification *e.g.*
  - > *radar antennas*

» remote control *e.g.*
  - > *robot arms*

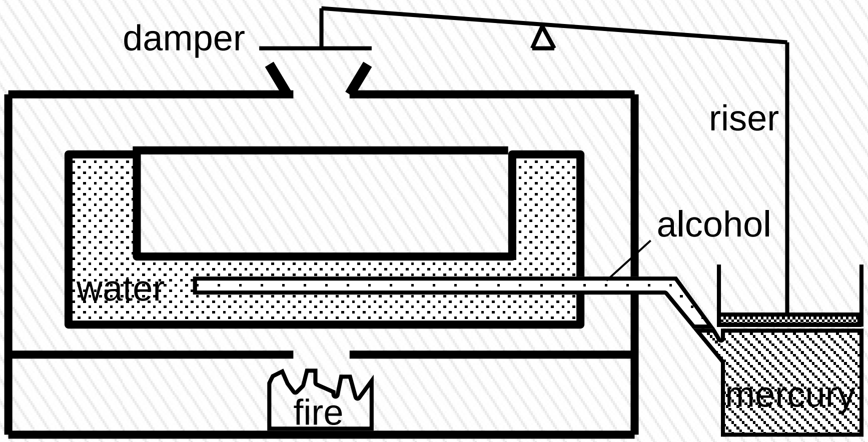
» convenience of input form *e.g.*
  - > *room temperature control (thermostat setting Þ heat)*

» compensation for disturbances *e.g.*
  - > *room temperature control (effect of opening a window)*
  - > *radar antenna (effect of wind etc.)*

» water clock (Persians and Greek, 300BC)

  - > required constant rate of water trickle
  - > achieved by float valve

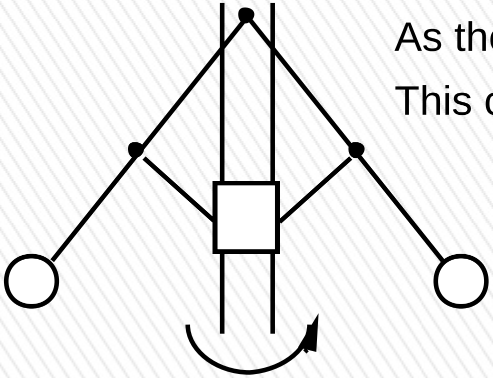
» Drebbel's incubator – 1620 – constant Temperature



Quick History

» Flyball governor - James Watt, 1788

> maintaining fixed speed on a steam engine so the speed is maintained constant – regulation



As the speed increases, the flyballs rise

This closes a steam valve to the engine

» stability stabilization James Clerk Maxwell, 1868

> beginnings of modern control theory

> derived conditions for stability in simple cases

History Contd.

- Followed by **E.R. Routh** - more general conditions for stability
  - Frequency response
  - Amplifiers needed for long distance communication in the 1920/30's
  - the distortion they introduced was too great
- **Black** proposed the *feedback* amplifier
- but the problem of instability arose again
- **Bode and Nyquist** introduced analysis based on frequency response
  - Proportional + Integral + Derivative Control
  - automatic ship steering
- **Sperry Gyroscope Co. 1922**
- **Root Locus - W.R. Evans, 1948**
  - Graphical technique suitable for analysis and design
  - developed for guidance and control of aircraft
- **Zadeh 1965** Fuzzy controllers
- Mechatronics and Microelectromechanical **(MEMS) 1990s**

History Contd.

» What defines dynamic system is the change (non-negligible) to systems parameters in time

behaviour – state

» Systems Modelling and Simulation for the purpose of:

- Understanding the behaviour in time
- Conduct what if scenarios
- Build if it does not exist.

Dynamic Systems & Systems Modelling

- Physical Models (prototypes)
- **Analytical Models** *(e.g. Differential Equations)*
- Numerical Models
- Experimental Models

Representation (Describing) system in mathematical terms

Type of Models

Response of an Analytical model to a physical input (excitations):

1. ***Time Domain:*** the response metric is expressed as a function of time →

   time denoted by ***t*** is the independent variable

2. ***Frequency Domain:*** the amplitude and the phase angle of response is expressed as a function of frequency →

   frequency denoted by **ω** is the independent variable.

Analytical Models

$$Transfer\ Function = \frac{Laplace\ transform\ of\ output\ variable}{Laplace\ transform\ of\ input\ variable}$$

e.g. mobility, admittance, impedance, and transmissibility

Transfer Function

Superposition Principle and Linear Systems

» Superposition Principle states that:

all linear systems' outputs at a given time and place caused by two or more input (excitation) is the sum of the responses which would have been caused by each individual input.

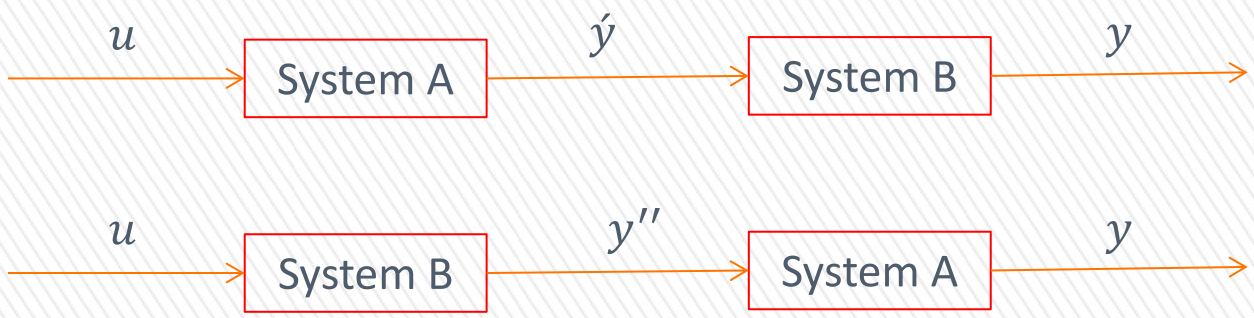
$$F(x_1 + x_2 + x_3 + \cdots) = F(x_1) + F(x_2) + \cdots \quad \textbf{(superposition)}$$

Input u_1 → System → Output y_1

Input u_2 → System → Output y_2

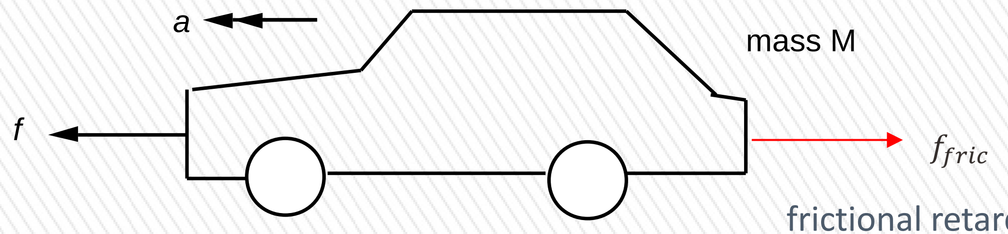
⟹ Input $a_1 u_1 + a_2 u_2$ → System → Output $a_1 y_1 + a_2 y_2$

» Linear Systems Interchangeability: sequentially component of system can be interchanged without affecting the output for a given input. (parallel system?)



Linear Systems Interchangeability

Example



frictional retarding force e.g. air resistance

Newton's second law: $f - f_{fric} = Ma$

Assume that frictional force is proportional to velocity (viscose friction) → $f_{fric} = Bv$ where B is the damping constant

Therefore : $f - Bv = M\frac{dv}{dt}$ or $\frac{dv}{dt} + \frac{B}{M}v(t) = \frac{1}{M}f(t)$

First order linear differential equation

1st order because the highest derivative is the 1st derivative

Example Cont. Solution 1st order linear Differential Eq.

» the car: $$\frac{dv}{dt}+\frac{B}{M}v(t)=\frac{1}{M}f(t)$$

» Include a function of time *x(t)*

$$x(t)\frac{dv}{dt}+\frac{B}{M}x(t)v(t)=\frac{1}{M}x(t)f(t) \qquad (1)$$

» Choose such that

$$x(t)\frac{dv}{dt}+\frac{B}{M}x(t)v(t)=\frac{d}{dt}\left[x(t)v(t)\right]=x(t)\frac{dv}{dt}+\frac{dx}{dt}v(t)$$

Example cont.

» To find *x(t)* note that $\frac{dx}{dt} v(t) = \frac{B}{M} x(t) v(t)$

» Separating the variables gives $\frac{1}{x} dx = \frac{B}{M} dt$

» Integrating both sides with appropriate limits:

$$\int_{x(0)}^{x(t)} \frac{1}{x} dx = \frac{B}{M} \int_0^t d\tau$$

$$\therefore \left[\log_e x\right]_{x(0)}^{x(t)} = \frac{B}{M} \left[\tau\right]_0^t$$

where *t* is an integrating variable.

$$\therefore \log_e x(t) - \log_e x(0) = \frac{B}{M} t$$

$$\therefore \log_e \left[\frac{x(t)}{x(0)}\right] = \frac{B}{M} t$$

Expressing both sides to the power *e*: $$\frac{x(t)}{x(0)} = e^{\frac{B}{M}t}$$

from which $x(t) = x(0)e^{\frac{B}{M}t}$

Returning to the main proof Eq. (1) becomes

$$\frac{d}{dt}\left[x(t)v(t)\right] = \frac{1}{M}x(t)f(t)$$

substituting for :

$$\frac{d}{dt}\left[e^{\frac{B}{M}t}x(0)v(t)\right] = \frac{1}{M}e^{\frac{B}{M}t}x(0)f(t)$$

Example Cont.

Example Cont.

Both sides of the equation can be divided by *x(0)*

$$\frac{d}{dt}\left[e^{\frac{B}{M}t}v(t)\right] = \frac{1}{M}e^{\frac{B}{M}t}f(t) \quad \text{or} \quad d\left[e^{\frac{B}{M}t}v(t)\right] = \frac{1}{M}e^{\frac{B}{M}t}f(t)\,dt$$

Integrating both sides over the time interval :

$$\int_{e^{\frac{B}{M}0}v(0)}^{e^{\frac{B}{M}t}v(t)} d\left[e^{\frac{B}{M}t}v(t)\right] = \frac{1}{M}\int_0^t e^{\frac{B}{M}\tau}f(\tau)d\tau$$

Evaluating the integrals gives:

$$e^{\frac{B}{M}t}v(t) - 1v(0) = \frac{1}{M}\int_0^t e^{\frac{B}{M}\tau}f(\tau)d\tau$$

So then

$$v(t) = e^{-\frac{B}{M}t} v(0) \quad + \quad \frac{1}{M} e^{-\frac{B}{M}t} \int_0^t e^{\frac{B}{M}\tau} f(\tau) d\tau$$

- Note the solution has 2 parts:
- free response (zero input)
  - due to initial conditions; always represents stored energy
- forced response (zero state)
  - depends on $f(\tau)$ for $0 \le \tau \le t$
  - i.e. the input signal over the time interval from zero to the present time.

Example Cont.

- » Mechanical
- » Electrical
- » Thermal
- » Fluid

Models
(energy storage and dissipation factors)

System Physical Characteristics

Across and Through Variables

- Across Variables: are measured across an element as the ***difference between the two ends*** *(e.g. velocity, temperature, voltage, pressure)*
- Through Variables: are constant ***properties that flows throughout the element*** *(e.g. force, current, flow, heat transfer rates)*
- Pending the most appropriate representation of the state variable of an element, the element can be *A-type* or *T-type* (for example in Mechanical system mass is A-type and spring is T-type)

» Inertia

Remember: $f = M\frac{dv}{dt}$ (1)

Power = *fv* = *rate of change of energy*

$$E = \int fv\,dt = \int M\frac{dv}{dt}v\,dt = \int Mv\,dv \qquad (2)$$

$$E = \frac{1}{2}Mv^2$$

Kenetic Energy

Mechanical Factors

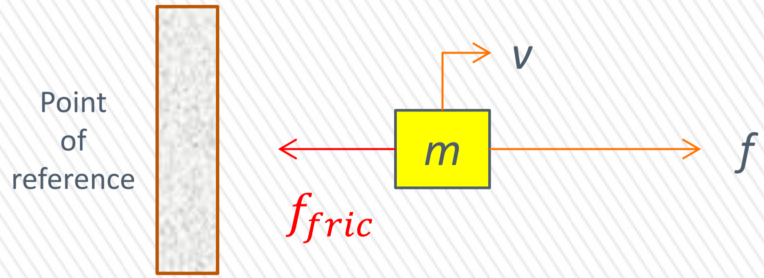
» By Integrating equation (2):

$$v(t) = \frac{1}{m}\int_{0^-}^{t} f\,dt \; + v(0^-) \qquad (3)$$

Whilst $t = 0^+$ and as long as force f is finite:

Instant just after *t=0*

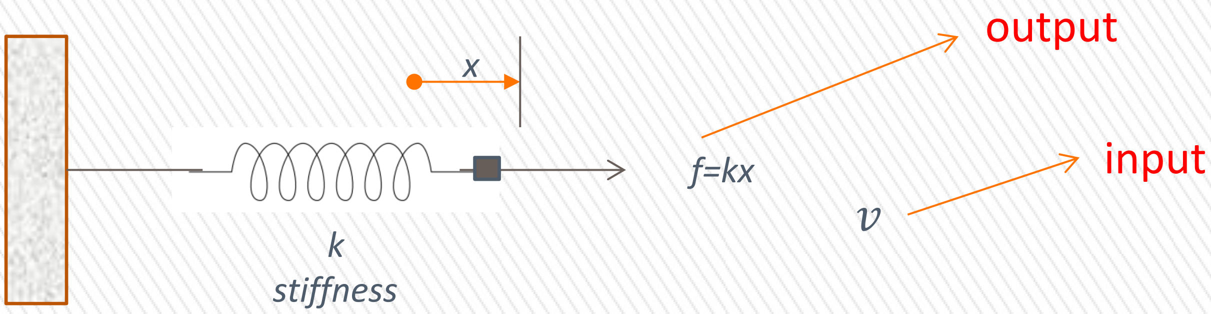
$$v(0^+) = v(0^-)$$



Kinetic Energy – Mass (inertia)

Inertia

- Inertia is an energy storage
- Velocity can represent the state of inertia, the relationship between velocity and applied can be determined at any time.
- Velocity across an inertia element cannot change instantaneously unless an infinite amount of force is applied.
- A finite force cannot cause infinite acceleration in an inertia element.
- Velocity is an A-Type variable thus inertia is an A-type variable.



- Hook’s Law: $$\frac{df}{dt} = kv \qquad (4)$$
- The energy of spring element can be expressed as:

$$E = \int fvdt = \int f\frac{1}{k}\frac{df}{dt}dt = \int \frac{1}{k}fdf \qquad (5)$$

Or

$$Energy\, E = \frac{1}{2}\frac{f^2}{k} \qquad (6)$$

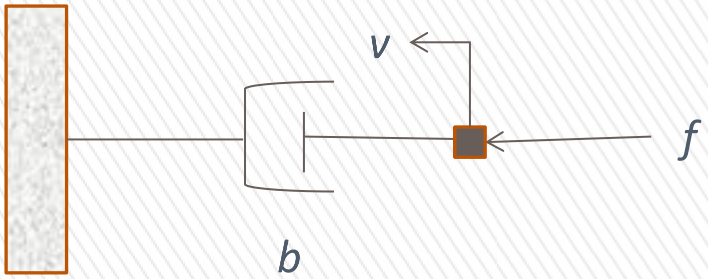
The Spring (Stiffness) element

We have differentiated the familiar force-deflection Hook's law in order to be consistent with the response/state variable (velocity)

Following the same steps as for inertia element, the energy of a spring element can be expressed as:

- Also known as potential energy $f(t) = k \int v dt + f(0)$
- A spring stiffness element is an energy storage element (elastic potential energy)
- Force can represent the state of a stiffness because at any time t the force can be determined. The energy can be represented by f alone.
- Force through stiffness cannot change instantaneously unless an infinite velocity is applied.
- Force f is the natural response (output) variable and velocity is the natural input.
- A spring is T-type.

The Spring (Stiffness) element



$$f = bv \qquad (7)$$

Where b is the damping constant.

Either f or v represent its state.

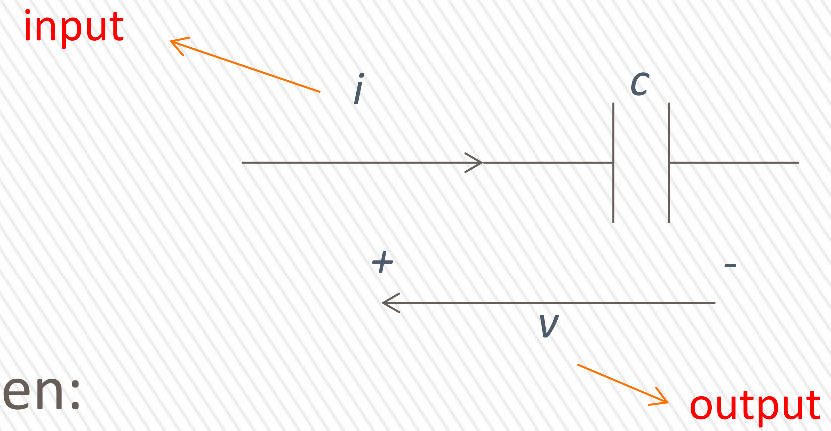
Damping Element (Energy Dissipation)

- Capacitor → *A-type*
- *Voltage* → across variable (as its state)
- Current → through variable
- Inductor → *T-type*

Energy Storage
Differential equations

- *Resistor as the energy dissipater (algebraic equation)*

Electrical Elements



$$C\frac{dv}{dt} = i \qquad (8)$$

Since power is given by vi, then:

$$E = \int iv\,dt = \int C\frac{dv}{dt} = \int Cv\,dv \qquad (9)$$

Or

$$E = \frac{1}{2}Cv^2 \qquad (10)$$

Electro static energy of a capacitor

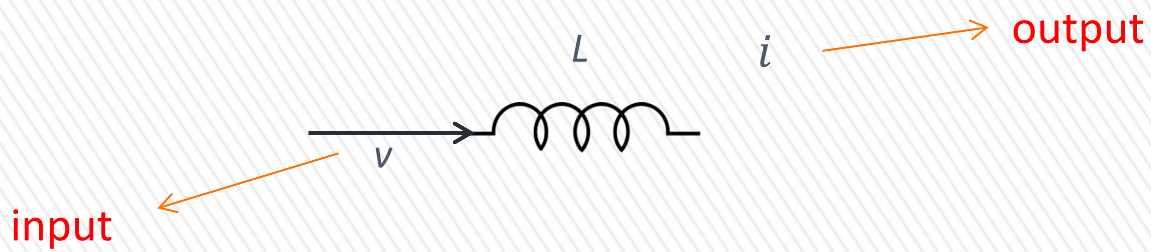
$$v(t) = \frac{1}{C}\int_0^t i\,dt \qquad (11)$$

Capacitor Element

Capacitor element described by differential equation.

- Capacitor is an energy storage element
- Voltage is the natural response (output) variable. Voltage at any time can be determined with the knowledge of initial voltage and the applied current values. The value of energy can be represented by the variable *v alone.*
- Voltage across capacitor cannot be changed instantaneously unless an infinite current is applied
- Voltage is the natural output variable and current is the natural input variable
- Since the state variable, voltage, is an across variable, a capacitor is an *A-type element.*

Capacitor



$$L\frac{di}{dt} = v \qquad (12)$$

$$Energy\ E = \frac{1}{2}Li^2 \qquad (13)$$

Electromagnetic energy of an inductor:

$$i(t) = \frac{1}{L}\int_0^t vdt + i(0) \qquad (14)$$

Inductor Element

$$v = Ri \qquad (15)$$

- » Either current or voltage could define its state
- » Algebraic equation
- » No new state variable (Why?)
  - > Because the state variables *v* is represented by an independent capacitor element, and *i* is established by an independent inductor element. Thus a damper element does not introduce new state.

Resistor Element (energy dissipater)

Today Discussions

1. Aim and Objectives
2. Structure and Assessments (deadlines and course work)
3. Introduction to Industrial Control Systems
4. Basic Electrical and Mechanical Models