Week 9
Lecture:
Topic 1: Control elements - Actuators
Topic 2: Time and frequency domain dynamics
Topics 3+4: Stability and PID control
Labs: Groups 1 & 2 Tue 2:10-4:00pm
Tutorial 7: Level, Density and Viscosity (next week)
Tutorial 8: Displacement, Velocity and Acceleration (next week)

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Topic 1: Final Control Elements - Actuators
- Learning outcomes:
  - Explain function of each block in a general block diagram of a feed-back (closed-loop) control system
  - Describe components of a control system: process (plant), transducers, recorders, comparison elements, controllers and final control elements

Learning Outcomes
- Explain function of each block in a general block diagram of a feed-back (closed-loop) control system
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- Explain DAQ and I/O Interface
- Reading Resources: Chapter 15 (LN) and Chapter 11 (Dunn, 2005)

General Structure of C.L.C.S

Example: Flow Control System

A closed-loop (feedback) process control system

Open-loop control system

Controller

Final Control

Process

Comparison element

Disturbances

Set-point R (Reference)

Controller

Final Control

Process variable (Output)

Signal conditioning devices (amplifiers) are used where necessary

Example: Flow Control System

Comparison element

Pneumatic Supply

4-20

Pump

Process variable (Flow)

Orifice

Rotameter

DC24V Supply

Computer, DAQ & Software

4-20
“Process/Plant” Block

- Representation of overall process
- Dynamic system in which process variable(s) is controlled or maintained at desired value(s).
- Examples: ship (rudder, course), fluid flow (input flow, output flow), boiler drum level control system, thickness control system, sun-tracking control of Solar Collectors, etc.
- Often represented by an ODE

“Transducer” Block

- Measurement of process variables
- A transducer is a device that converts the quantity being measured into an optical, mechanical, or more commonly – electrical signal. The energy-conversion process that takes place is referred to as transduction.
- Examples: Resistance Displacement Transducer, Pressure Bellows, Force Diaphragm, Pressure Flapper-Nozzle

Transducers

- Most transducers consist of a sensing element and a conversion or control element, as shown in the two-block diagram

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Sensing Element  Conversion or C/E
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Primary signal  Transducer output signal

Electrical transducers:
- Variable control parameter types consist of resistance, capacitance, inductance, and mutual-inductance type
- Self-generating types consist of electromagnetic, thermoelectric, photoemissive, and piezo-electric types

Transmitters

- Transmitters are the devices that are designed for purpose to receive a process variable signal at the transducer (sensor) and give this signal enough power so that it can be transmitted over the necessary distance without the addition of excessive noise or reduction in accuracy, sensitivity, and other factors.

Transmitters

- A list of some of the more popular (unofficial) industry standards:
  - Current ranges: 1-5mA, 4-20mA, 10-50mA
  - Low-level voltage ranges: 0-50mV, 0.25-1.25V
  - High-level voltage ranges: 0-1V, 0-5V, 0-10V, -5-+5V, -10-+10V
  - Pressure ranges: 3-15psi, 0-100 kPa

Examples of transmitters used in industries:
Transmitters

- A list of different types of transmitters:
  - Thermocouple transmitters,
  - Millivolt transmitters,
  - RTD (Resistance Temperature Detector),
  - Potential-to-Current Transmitters,
  - Strain gauge transmitters,
  - Isolated-type transmitters,
  - Electrical-to-pneumatic transmitters,
  - AC current-to-dc current transmitters,
  - Frequency-to-current transmitters,
  - Square-root transmitters, etc.

“Recorder” Block (Indicating Devices)

- Indicating units (recorder, display) are the devices that indicate the variables being measured. The indicating devices are used to show an operator the variables that should be observed regularly.
- Mechanical Pointers (Pressure Gauge)
- Display (CRT, LCD)
- Recorder (Pen, Chart, Magnetic Tape, Ultra-violet, Printer, PC and Software, etc.)
- Measurement application software (virtual instrument software: LabVIEW, MATLAB/Simulink)
- Examples of Indicating Devices: pressure gauges, gyrocompass repeaters, rudder indicators, pitch angle indicator, level indicator, etc.

“Comparison Element” Block

- Comparison element compares the output or controlled variable with the desired input or reference signal and generates an error or deviation signal. It performs the mathematical operation of subtraction.
- Examples: Differential lever, Potentiometer, Synchro, Operational Amplifier...
- Comparison elements can be divided into mechanic (differential levers), electrical & electronic (potentiometers, synchros, operational amplifiers), etc.

“Controller” Block

- “Brains” of the control system
- Controller is a device that synthesizes a control law from the errors and generates control signals.
- As far as we are concerned, the controller is considered as a device producing an amplified and conditioned signal proportional to the error.
- Controllers can be divided into different categories depending on the nature of the signals processed in it, such as hydraulic controller, electrical controller, etc.
- Examples: Error amplifiers, PID Controller, Optimal Controller, etc.

“Final Control Element” Block

- Part that converts the signal from the controller into actual variations in the controlling variable
- Final control elements are those elements in which the amplified and conditioned error signal (controlling signal) is used to regulate some energy source to the process.
- Examples: Valve actuators, hydraulic servo-valves, hydraulic actuators, D.C servo-motors, A.C. servo-motors, stepper motors, etc.

Introduction to Components

- Process/Plant
- Transducers/Transmitters
- Indicators/Recorders
- Comparison Elements
- Controllers (PID)
- Final Control Elements (Valves, Motors)
Comparator

- Differential levers (walking beams): mechanical elements which are used in many pneumatic elements and in hydraulic control systems.

\[ \varepsilon = \frac{b}{(a+b)} x - \frac{a}{(a+b)} y \]

\[ \varepsilon = \frac{1}{2}(x - y) \]

Comparator

- Potentiometers: Potentiometers are used in many d.c. electrical positioning servo-systems.

\[ \varepsilon = K_p (\theta_1 - \theta_0) \]

Synchros are used for comparison of the input and output rotations in a.c. electrical servo-systems and rotating hydraulic systems.

Output = \( K(\theta_1 - \theta_0) \)

Operational Amplifiers (op-amps)

- Operational amplifiers are direct-coupled (dc) amplifiers with special characteristics. They can be used for error detection by employing the following circuit:

\[ v_o = - (v_1 - v_2) \]

Microprocessor-based Controllers

- PID Controller (pneumatic, hydraulic, electric/electronic, computer-based)
- Input is error, output is control signal
- Other types of controller: optimal controller, self-tuning controller, fuzzy controller, etc.

DigiTech PID Controller

Final control elements - Actuators

- Function: convert control signal to a signal that has enough energy
- Classification:
  - Electric actuators (DC motors, AC motors and Stepper Motors) (flow, level, velocity)
  - Pneumatic actuators – Diaphragm valve (flow, level)
  - Hydraulic actuators – Electro-hydraulic servo valve (flow, governor, rudder)
Diaphragm Control Valve

**Principle:**
\[ x = \frac{A}{k} p_i, \quad q_i = K_x x \]

**Application:** IP Converter
Pneumatic supply

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Different types of valve

- Fail-open (Air-to-close)
- Fail-closed (Air-to-open)

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Hydraulic control valves

- Hydraulic systems (hydraulic and electro-hydraulic, pneumatic)

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Electro-hydraulic Servo Valve

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Final Control Element

- Electrical element: DC Servo Motor

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Permanent Magnetic DC Motor

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DC Motor

- Block diagram of a DC motor system

\[ \Theta_n(s) = \frac{K_i}{E_s(s)} \]

- Transfer function without load (\( T_L = 0 \))

\[ \Theta_n(s) = \frac{1}{L_s J_n s^2 + (R_s J_n + B_m L_s) s + (K_n K_i + R_s B_m) s} \]

DC Motor – Velocity control

- Arrangement
- Tachometer or Encoder to measure speed

DC Motor – Position control

- Block diagram

Final Control Element

- Electrical element: AC Servo Motor

Applications of Actuators

Applications - Marine Hydraulic Steering

http://www.pirate4x4.com/
Applications - Marine Hydraulic Steering

- Steering system of marine vehicle:

Example: Thickness Control System

Example: Thickness control system

Example: Level control system

Boiler water level control system

Example: Autopilot

http://www.spiraxsarco.com
Eg: Guidance, Navigation & Control

Weather Routing

Way-Points

Guidance System

Autopilot

Control Allocation

Estimated Position and Velocities

Control System

Ship

Weather Data

Waves, Wind, Currents

Navigation System

Thor I. Fossen, 2002

Example

A marine engine governor has a transfer function as shown below, where the input is fuel flow rate and the output is rotational speed. A d.c. motor (valve motor) is used to control the fuel valve. It has input of voltage, and output of fuel flow rate. A PI controller for the motor with control gains \( K_p \) and \( K_i \). A tachometer in the feedback loop measures the rotational speed and feeds back with gain of 5. Find the total feedback transfer function. (Try with PID controller)

\[
\frac{E}{y(t)} = \frac{1}{s} \frac{1}{s+1} \frac{1}{5(s+5)}
\]

Computer-based Control and Data Acquisition/IO Interface

• Computer-based instrumentation and control systems
• Data Acquisition – I/O Interface
• Virtual Instrument Software for logging, analysis, control:
  – MATLAB/Simulink – Mathworks
  – LabVIEW – National Instruments
  – RT-LAB – Opal RT
  – Etc.

Computer controlled system

How to connect: bus and LAN

• Software (logging, analysis, monitoring, control)

GPIB = General Purpose Interface Bus IEEE-488
How to connect: bus and LAN (network)

Components of a computer controlled system

Wireless and RT techniques
- Real-time control

Data Acquisition/IO Interface
- Mathworks – MATLAB/Simulink

National Instruments - LabVIEW

NI – DAQ & LabVIEW

www.ni.com
http://techteach.no/labview/lv85/labview/index.htm
Summary of Topic 1
• General structure of a control system
• Elements of Control Systems: Process/Plant, Transducer/Transmitter (Measurement), Recorder/Indicating Devices, Comparison Element, Controller, Final Control Element,
• Examples of control systems
• Current trend of control components: Digital techniques - Computer-based control elements – DAQ and I/O Interface

Any Questions?

Topic 2: Time and frequency domain analysis
• Dynamic performance
  – Test input: system response
• Time domain
  – Step function (step response)
  – Ramp function (ramp response)
  – Impulse function (impulse response)
• Frequency domain:
  – Sinewave (frequency response)
• Time delay, steady state error and disturbances
• Reading: Chapter 16

Dynamic Performance
• Zero order, first order, second order
• Step input, ramp input, sine-wave input
  Step \( F(s) = L\{A\} = \frac{A}{s} \)
  Ramp \( F(s) = L\{At\} = \frac{A}{s^2} \)
  Sine-wave \( F(s) = L\{\sin \omega t\} = \frac{\omega}{s^2 + \omega^2} \)

Time Domain Analysis
• Step Responses:
  – Zero order systems (ideal, linear)
  – 1st order systems
  – 2nd order systems
• Step Response Specifications

Unit step response of 1st order sysems
\[
Y(s) = \frac{1}{10s + 1}
\]
The smaller the time constant is, the faster the system response is.
Unit step responses of 2nd-order sys

Specifications of step response

Step responses with different N.F

Step Response
- Analytic method
- Laplace method
- Numerical methods (MATLAB/Simulink)
  \[ H(s) = \frac{5}{s^2 + 3s + 5} U(s) \]
- MATLAB: step(num,den)
- Simulink: Step Block + Transfer Fcn Block

Frequency Domain Dynamics
- Analytic method
- Laplace transform
- Numerical method
  \[ G(s) = \frac{Y(s)}{U(s)} = \frac{5}{s^2 + 3s + 5} \]
- Control theory
- Nyquist diagrams
- Bode diagrams
- Nichols diagrams

Frequency Domain Analysis
- \( s = j\omega \)
- \[ G(j\omega) = \frac{Y(j\omega)}{U(j\omega)} \]
- \[ G(j\omega) = \text{Re}[G(j\omega)] + j\text{Im}[G(j\omega)] \]
- Magnitude = \(|G(j\omega)|\), Phase = \(\angle G(j\omega)\)
- Polar plot or Nyquist plot (nyquist – LTI)
- Logarithmic plot or Bode plot (bode – LTI)
- Log-magnitude versus phase plot (nichols - LTI)
- LTI = linear time invariant
**Frequency Specifications**
- Resonant Peak $M_r$
- Resonant Frequency $\omega_r$
- Bandwidth $BW$
- Cutoff Rate

**Time delays**
- Pure time delays may be encountered in various types of systems, especially systems with hydraulic, pneumatic, or mechanical transmissions.
- Systems with computer control also have time delays since it takes time for the computer to execute numerical operations.
- The output will not begin to respond to an input until after a given time interval
- Examples of systems with time delays

**Diagram of Time Delays**

- Solution A
- Solution B
- Valve
- Metering point
- Steel plate
- Roller
- Thickness measuring gauge
- $y(t)$
- $v$
- $d$
- $b(t)$

**Example of system with time delays**

**Approximation of time delays**
- Maclaurin series
  
  \[ e^{-T_d s} \approx 1 - T_d s + \frac{T_d^2 s^2}{2} - \frac{(T_d s)^3}{6} - \ldots \]

  \[ e^{T_d s} \approx \frac{1}{1 + T_d s + \frac{T_d^2 s^2}{2} + \frac{(T_d s)^3}{6} + \ldots} \]

- Padé approx:
  
  \[ e^{-T_d s} \approx \frac{1 - \frac{T_d s}{2}}{1 + \frac{T_d s}{2}} \]

- Example of system with time delays
Procedures to find S.S.Es

• See P. 342
• Example 16.5: S.S.E with step input p.344
• Example 16.6: S.S.E with ramp input p.346

Disturbances

Disturbance is any change inside or outside the control system, which upsets the equilibrium. Disturbances can be:

- A change in the set point;
- A change in the load on the system;
- A change in the characteristics; and
- A change in the ambient conditions…

Examples of disturbances:

- Ship motion control system: any change of environment (wind, waves and currents) affecting on ship’s course;
- Electronic control system: change in system load; noise due to components
- Temperature control system: change in temperature signal because of energy transfer or error of sensor; etc.

Example: Disturbance

Simulation of Autopilot with disturbances
Methods to Reduce

It is difficult to measure and predict disturbances. In design of control systems, effects of disturbances should be considered.
- Reduction at source: process design (p.349)
- Reduction by local feedback (p.349)
- Reduction by feed-forward (p.350)
- Reduction by prediction (p.351)

Summary of Topic 2

- dynamic performance (step, ramp and frequency responses)
- time delay
- steady state error
- disturbances

Any Questions?

Tutorial

- Tutorial 7: any questions?
- Tutorial 8: Displacement, Motion Sensors