EDEXCEL NATIONAL CERTIFICATE/DIPLOMA
SCIENCE FOR TECHNICIANS

OUTCOME 4 - CLOSED-LOOP ENGINEERING SYSTEMS

4 Closed-loop engineering systems

Principles: definitions, system boundaries, inputs/outputs, sub-systems, signals, signal modification and conversion, system block diagram representation, closed-loop, system types, system characteristics and engineering uses

Systems *and* sub-systems: e.g. electronic, mechanical, fluid amplifiers; transducers as energy conversion devices and system actuation components

You should judge your progress by completing the self assessment exercises.

If we studied all the science necessary to cover this section of the syllabus, we would have enough material for a whole course. Only the basic elements can be realistically covered.

1. BASIC SYSTEM THEORY

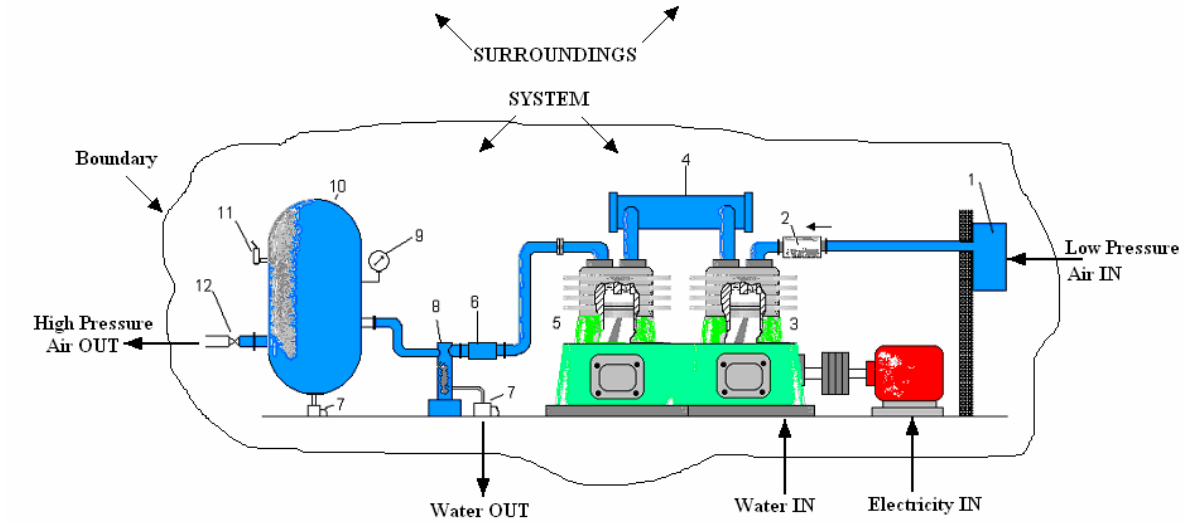
The concept of a system is very useful for explaining how something works. This applies to all forms of systems whether it is a management system, a manufacturing system, a biological system and so on. We are mainly concerned here with engineering systems such as

- Control systems (e.g. a robot control system)
- Thermodynamic systems (e.g. central heating system)
- Mechanical system (e.g. a gear box)
- Electronic system (e.g. television)
- Electric system (e.g. household lighting circuit)
- Fluid system (e.g. water supply network)
- Instrument system (e.g. a temperature gauge)

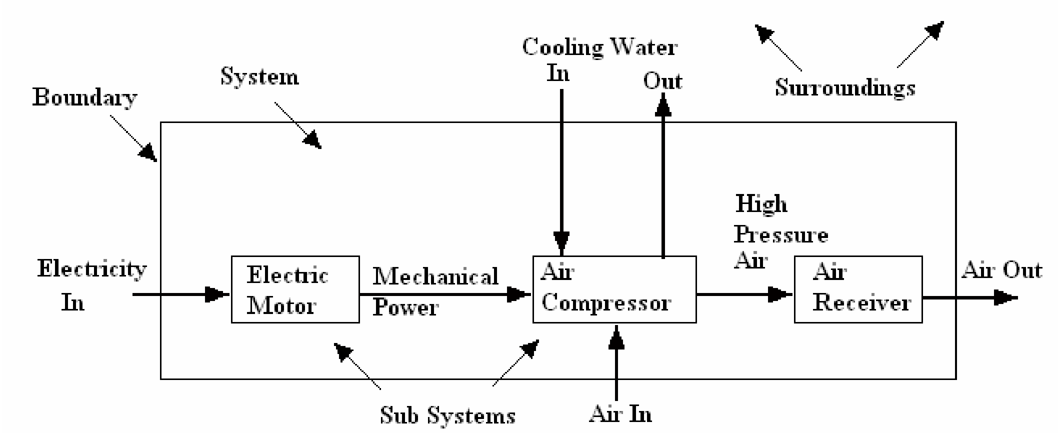
This section is mainly about instrument and control systems but first let's look at systems in general.

2. SYSTEM BOUNDARY

We can keep account of what goes in and out of a system by drawing a boundary around it. Outside the boundary we have the surroundings. This is particularly important in thermo – fluid systems so that we can apply the law of energy conservation and mass conservation. The diagram below illustrates how we can account for all the things entering and leaving an air compressor.



The schematic diagram above may be turned into the block diagram below. This is a tidier diagram and it may be broken down into smaller ***SUB SYSTEMS*** in order to make it easier to explain.
Each sub system has an output, which is passed on to become the input of another sub system. The arrows connecting them are called ***INTERACTIONAL FLOW PATHS***.



WORKED EXAMPLE No. 1

The air compressor described previously has a motor that consumes 10 kW of power. The cooling water flows at 2.5 kg/s and enters at 10°C and leaves at 35°C. The specific heat capacity of water is 4.186 kJ/kg K. Calculate the energy added to the air. Assume there is no other energy lost to the surroundings.

SOLUTION

We need to balance the energy entering and leaving the system boundary. Let the energy in the air at entry be E_1 and at exit be E_2.

Energy entering

Air	E_1
Water	$m\,c\,\theta = 2.5 \times 4.186 \times 10 = 104.7$ KJ/s
Electricity	10 000 kJ/s

Total = $E_1 +$ 10104.7 kJ/s

ENERGY LEAVING

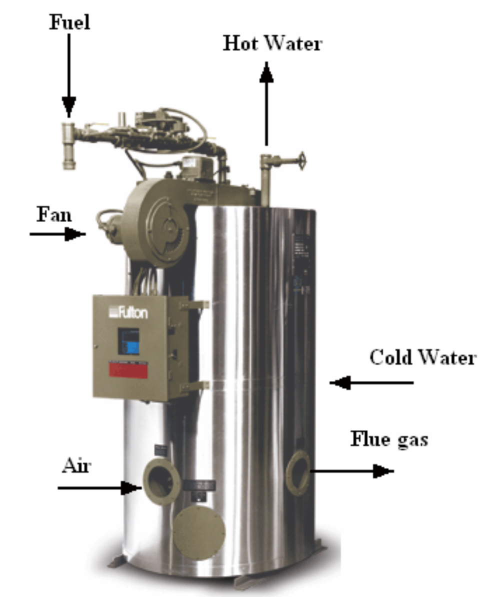
Air	E_2
Water	$m\,c\,\theta = 2.5 \times 4.186 \times 35 = 366.3$ KJ/s

Total = $E_2 +$ 366.3

The energy entering and leaving must be the same so $E_1 + 10104.7 = E_2 + 366.3$

The energy added to the air is $E_2 - E_1 = 10104.7 - 366.3 = 9738.4$ kJ/s

SELF ASSESSMENT EXERCISE No.1



The picture shows a small industrial oil fired hot water boiler.
The boiler has a fan that blows in air at a rate of 0.3 kg/s.
There is a fuel pump that pumps in oil at 0.02 kg/s.
The fuel liberates 45 000 kJ for every kg burned.

The burned gas leaves through the flue.
3 kg/s of cold water flows through a coiled copper tube and heat is exchanged between the hot burned gas and the water. The water temperature is raised by 68K.
The specific heat capacity of the water is 4.186 kJ/kg K.

Draw a block diagram of the system showing all the sub systems.

Label all the connections between blocks.

Assume no heat is lost to the surroundings. Calculate:

i. The mass of flue gas leaving per second. (0.32 kg/s)

ii. The approximate energy in the flue gas relative to the energy of the air entering. (46 kJ/s)

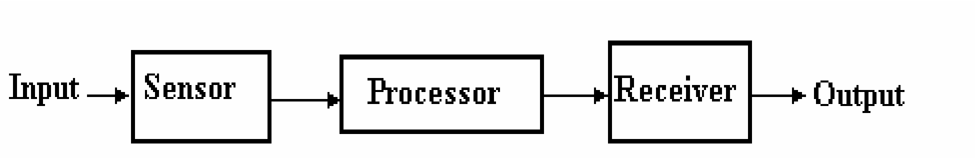
3. INSTRUMENT SYSTEMS

This topic could cover a whole module so it is only possible to give a brief introduction. An instrument system could be analogue or digital and it is beyond the scope of this tutorial to cover digital principles. Things that we commonly measure are:

Temperature	**Pressure**
Speed	**Flow rate**
Force	**Movement, Velocity and Acceleration**
Stress and Strain	**Level or Depth**
Mass or Weight	**Density**
Size or Volume	**Acidity/Alkalinity**

A basic instrument system consists of three elements connected in series:

i SENSOR or INPUT DEVICE
ii SIGNAL PROCESSOR
iii RECEIVER or OUTPUT DEVICE



3.1 SENSORS

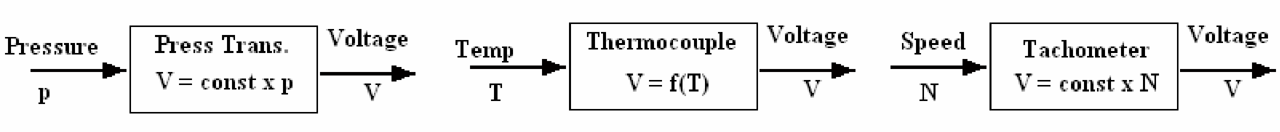
The sensor is a transducer that converts the signal being measured into a form suitable for processing. Here are some examples.

Pressure Transducer

Thermocouple

Tachometer

All these examples produce an electrical output. There are mathematical models for all these and these can be shown on a block diagram.



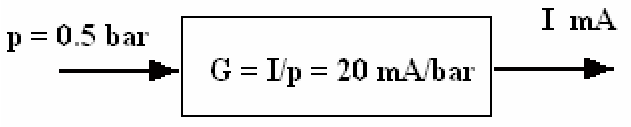
The mathematical model may be a simple constant or it may be a more complicated function.

Usually such sensors are called **PRIMARY TRANSDUCERS.**

When the ratio of the output to the input can be written as an equation we use a symbol such as G to denote it. This is illustrated in the next example.

WORKED EXAMPLE No. 2

A pressure transducer is shown in block form. Calculate the output current.

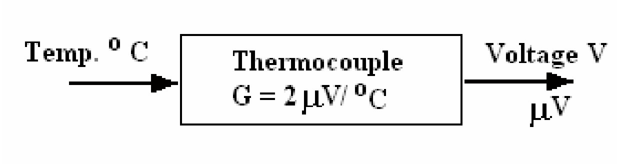


SOLUTION

G = I/p = 20 mA/bar $\qquad$ I = 20 p = 20 x 0.5 = 10 mA

WORKED EXAMPLE No. 3

A block diagram of a temperature transducer is shown. Find the output voltage when the input is 50°C.

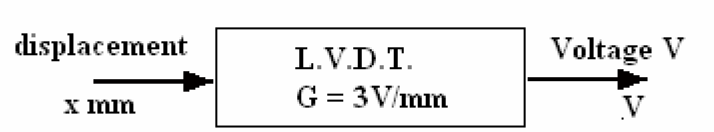


SOLUTION

G = V/θ = 2 μv/°C $\qquad$ V = 2θ = 100 μV

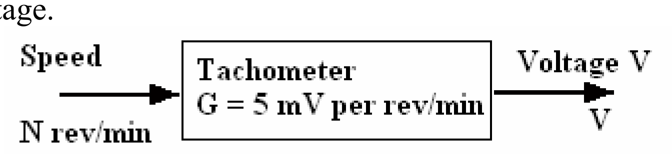
SELF ASSESSMENT EXERCISE No. 2

1. The block diagram shows the data for a Linear Voltage Displacement Transducer. The input is a displacement of 2 mm. Find the output volatge.



(Answer 6 V)

3. The block diagram shows details of a tachometer. The input is a speed of 250 rev/min. Find the output voltage.



(Answer 1.25 V)

3.2 **PROCESSORS**

ELECTRO - PNEUMATIC

The processor changes the signal into a form suitable for sending to the receiver. This is normally 4 to 20 mA for electrical equipment and 0.2 to 1 bar for pneumatic equipment.

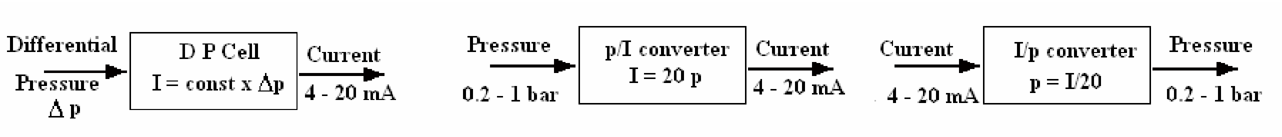
Here are some examples of processors. It might be a good exercise to find out more about what they are used for.

Differential Pressure Cell

Current to Pressure Converter (I/P)

Pressure to Current Converter (P/I)

Here are the models.

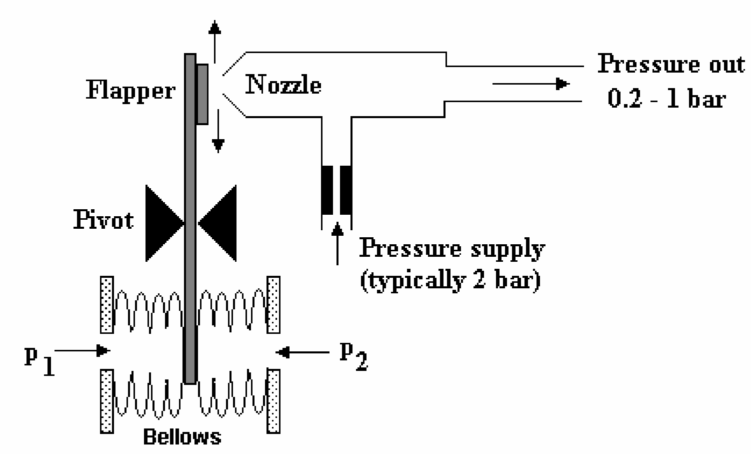


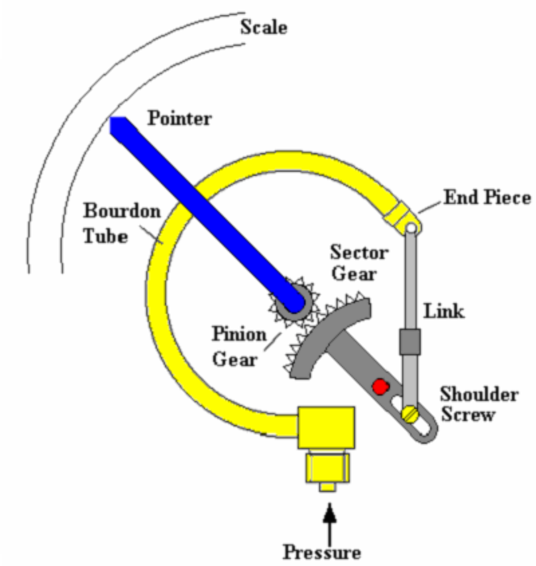
Usually such processors like these are called **SECONDARY TRANSDUCERS**.

MECHANICAL

Gears and Levers are widely used in processing mechanical signals to change the rotation or movement. For example you will find these elements in a D. P. Cell and in a Bourdon Pressure Gauge (see picture right).

Here is a schematic of a pneumatic Differential Pressure Cell and a Bourdon Pressure gauge.

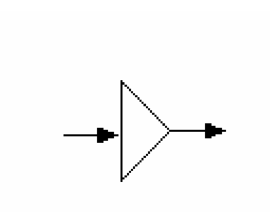




The nozzle and flapper is an example of a fluid amplifier where a small mechanical movement produces a large pressure change.

ELECTRONIC

There area vast range of electronic processors. One important one is the electronic amplifier.



Amplifiers may amplify VOLTAGE, CURRENT or BOTH in which case it is a POWER AMPLIFIER.

Amplifier gain may be expressed as a ratio or in decibels. The letter W indicates it refers to power gain. The gain in dbW is given by

$$\text{Gain(dbW)} = 10\log_{10}\frac{\text{Power Output}}{\text{Power Input}}$$

Other examples are :

ATTENUATORS – The opposite of an amplifier (e.g. a resistor) G is negative.
FREQUENCY CONVERTER – changes frequency into a voltage or current.
A/D CONVERTER - Converts Analogue voltage or current into digital electronic form.
D/A Converter – Reverses the process.

3.3 SIGNAL RECEIVERS

The variable (temperature, pressure, speed etc.) is measured with a sensor, processed and then sent to the receiver. Typical receivers are:-

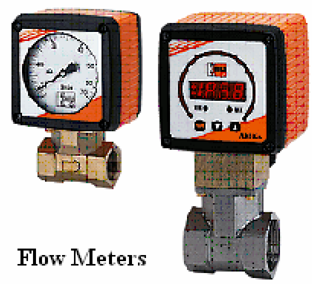
Display unit to show the value.
Recording/Storage device
Alarm
Computer
Modem for onward transmission.
Part of a controller.

The diagram shows a range of recorders.

COMPLETE SYSTEMS

Sometimes a complete instrument system may be contained in one package like the Bourdon pressure gauge. Other examples are temperature gauges and flow meters.

Temperature Gauge

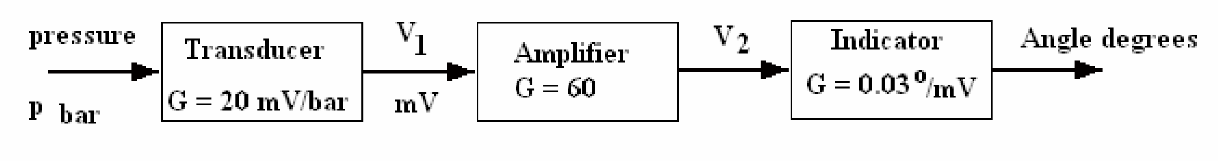


Flow Meters

Whether everything is in one package or made from individual modules linked together, the complete instrument system is made up from several sub-systems connected in series. The best way to deduce the input or output of a complete system is a step by step analysis of the information passing through.

WORKED EXAMPLE No. 4

The block diagram shows data for a complete system. The pressure transducer produces a millivolt output. This is amplified and sent to an indicator. The needle on the indicator rotates through an angle to indicate the pressure on a scale. Calculate the pressure when the angle of rotation is 90°.



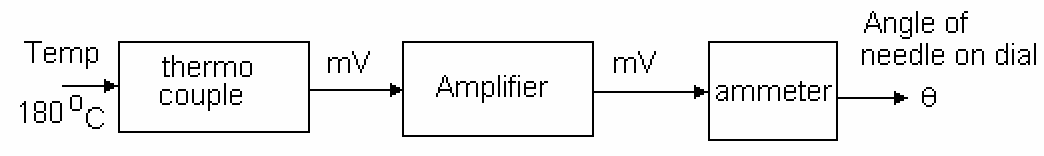
SOLUTION

Working backwards $V_2 = 90/0.03 = 3000$ mV
$V_1 = 3000/60 = 50$ mV
$p = 50/20 = 2.5$ bar

SELF ASSESSMENT EXERCISE No. 3

1. Find the output rotation for the temperature system below. The equations for each sub-system are as follows.

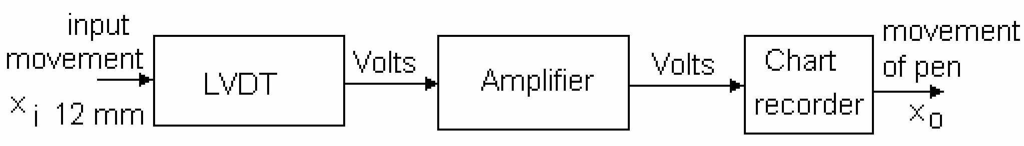
Thermocouple 3 mV per °C.
Amplifier gain 5
Meter 0.02° per mV



(Answer 54°)

2. An LVDT output is amplified and connected to a chart recorder. The block diagram is shown. Calculate the output movement of the chart recorder pen. The equations for the sub- systems are

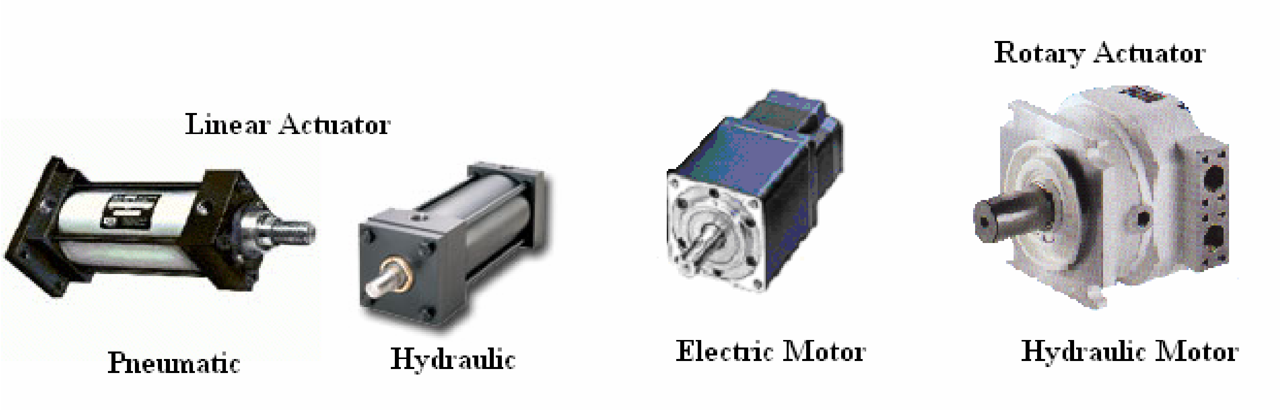
LVDT V = 0.2 V/mm
Amplifier gain = 4
Chart recorder $x_o = 5$ mm/V



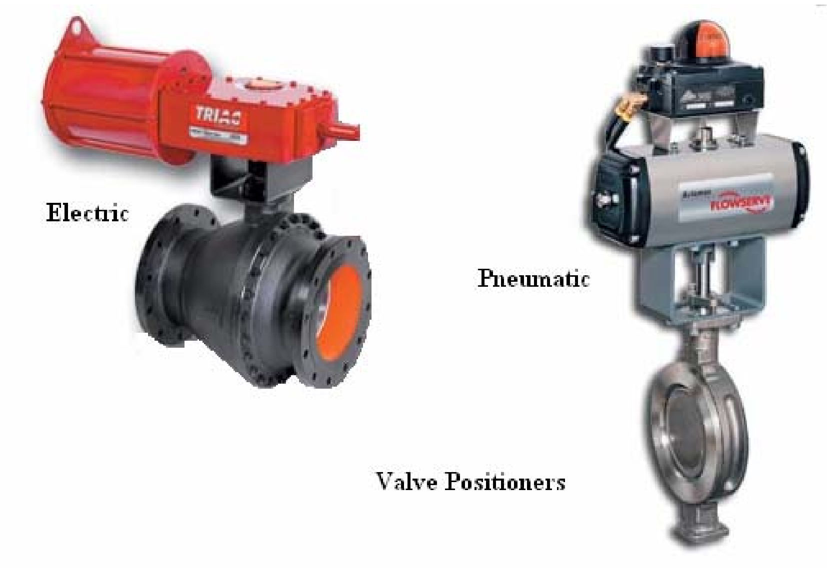
(Answer 48 mm)

4. OPEN LOOP CONTROL SYSTEMS

These are systems where an actuator is controlled manually. There is not sufficient study time to examine more than a brief sample. Here are some of the many actuators used in industry to move things.

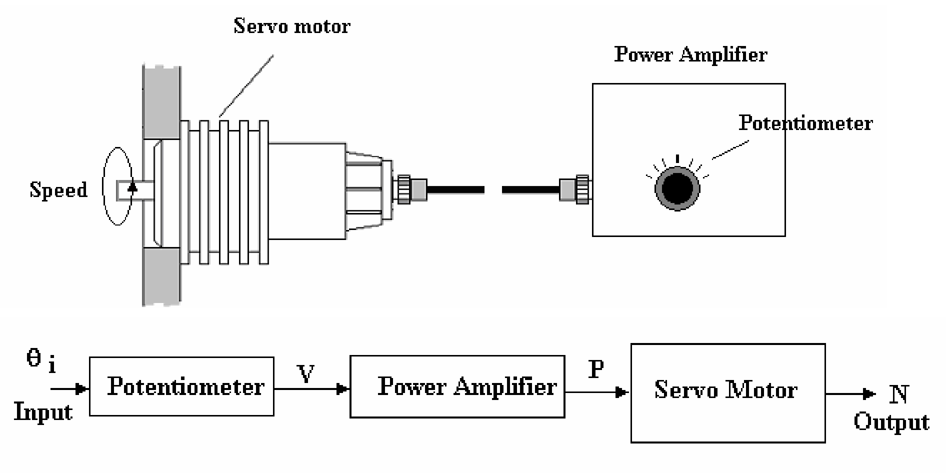


The diagram below shows an electric and pneumatic valve positioner used to control the flow of fluids in a pipe line.



ELECTRIC EXAMPLE

In this example the speed of an electric motor and is controlled. The speed is set by a potentiometer and the small voltage produced is changed into a powerful electric current to drive the motor.
The block diagram looks like this.

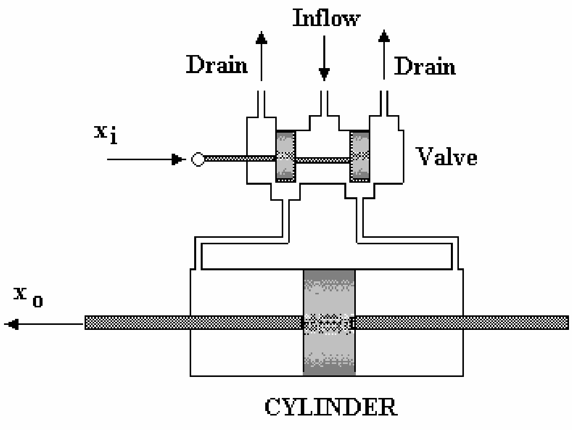


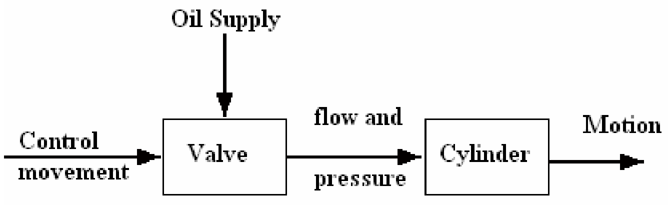
Note that we do not include blocks for the electricity supply system but we could if we wished to study it.

The block diagram show that the signal path from input to output is a linear chain not forming any loop so this why it is called an OPEN LOOP SYSTEM.

HYDRAULIC/PNEUMATIC EXAMPLE

The actuator is a cylinder that produces linear motion. It is moved by pumping fluid into one side or the other of the piston. The valve is manually controlled and moved to reverse the direction of flow.



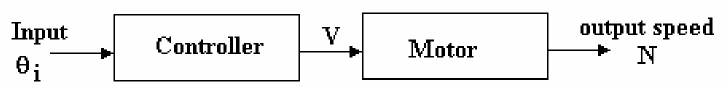


The block diagram only shows the control path. It is not usual to include the blocks for the fluid supply system and pump unless we are studying it. The block diagram is again an open chain or loop.

WORKED EXAMPLE No. 5

1. The speed of an electric motor is directly proportional to voltage such that N = 20V where V is in Volts and N in rev/min. The motor is controlled by a power supply which has an output voltage related to the position of the control knob by V = 2 θ_i where V is in Volts and θ_i is in degrees. Draw the block diagram and deduce the overall transfer function. Determine the output speed when the knob is set to 60^o.

SOLUTION



$G = N/\theta_i \quad = 2\theta_i \;\; x\ 20 = 40$ rev/min per degree   N = 40 x 60 = 2400 rev/min

SELF ASSESSMENT EXERCISE No. 4

1. A simple control system consists of a potentiometer with a transfer function of 0.02V/mm in series with an amplifier with a gain of 12, in series with a V/I converter with a transfer function I = 0.5V where V is in volts and I in mA. The output current is amplified with a gain of 1200 and the output current supplied to an electro-magnetic torque arm which produces 3 Nm per Amp. Draw the block diagram and deduce the overall transfer function. (0.432 Nm/mm)

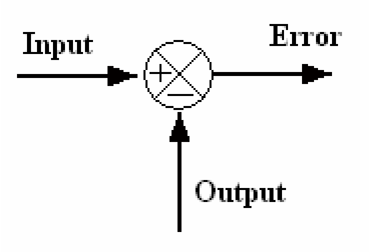
   Determine the input position of the potentiometer in mm which produces a torque output of 60 Nm.

   (138.9 mm)

5. CLOSED LOOP CONTROL SYSTEMS

Closed loop systems are used when automatic control or regulation is required.

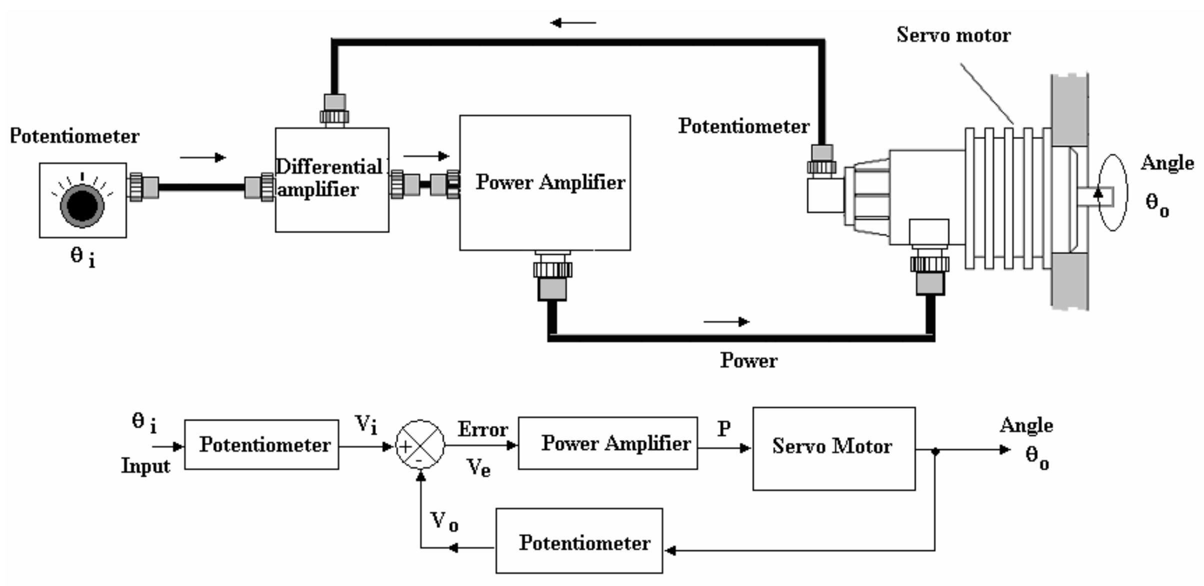
In order to regulate any control system we must determine the error between the output and the input. This is done with a summing device and the symbol for this is shown in the diagram. These devices may be electrical (e.g. a simple differential amplifier), pneumatic (e.g. a differential pressure cell) or mechanical. We can put a Plus (+) or minus (-) sign in the symbol to show if it is adding or subtracting.



ELECTRICAL EXAMPLE

Consider the example of the servo motor again. Suppose the motor drives a load and that the load suddenly increases. This would make the motor slow down as there would not be enough power to keep it at the original speed. We would now have an error between the speed selected with the potentiometer and the actual speed of the motor. To bring the speed back to the correct value, we have to turn up the power and to do this automatically we need a closed loop system. Open loop systems are incapable of maintaining a correct output in all but the simplest cases.

Suppose we wish to control the angle of the shaft θ_o. The input potentiometer produces a voltage V_i and the output potentiometer produces a voltage V_o to represent the angle of the shaft. If the two voltages are the same, the shaft is at the correct angle. If there is an error, the voltages are different. The differential amplifier acts as the summing device and produces a voltage V_e representing the error. The error is supplied to the power amplifier and power is sent to the motor to rotate it in the direction that corrects the angle. When the voltages are equal again, the error is zero and no power is supplied to the motor so it stops. Error in either direction can be corrected if the power amplifier is capable of producing positive and negative current.



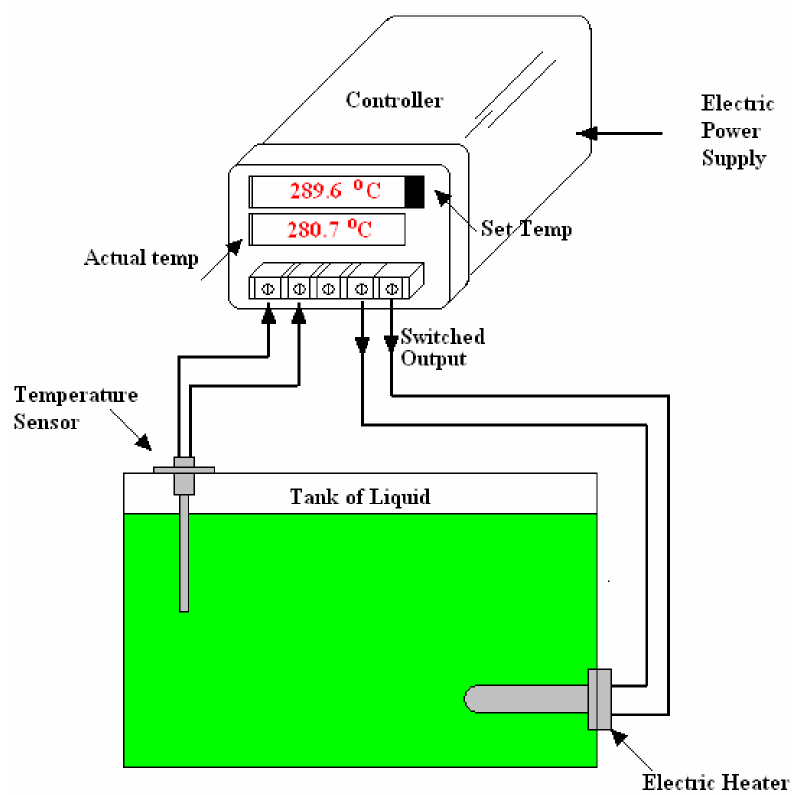
This description is somewhat over simplified and does not explain an actual working system. The motor would have difficulty staying at the correct angle if there is a load trying to turn it.
Note how the voltage from the output potentiometer is fed back to the summing device so that the error is $V_e = V_i - V_o$.

This is **NEGATIVE FEEDBACK** and this is essential to make the system respond to the error.

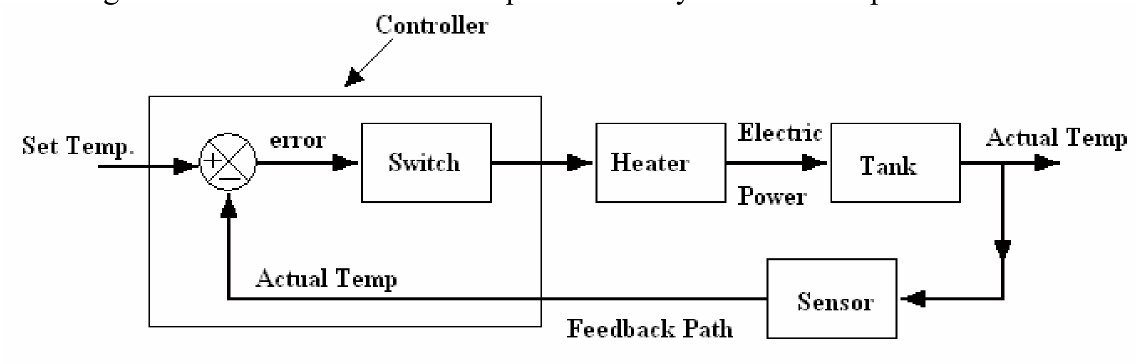
Also note how the signal path on the block diagram forms a closed loop which gives the name **CLOSED LOOP SYSTEM**

THERMAL EXAMPLE

The diagram shows a simple thermostatically controlled heater for a tank of liquid. The controller supplies electric power to the heater. The sensor feeds back the temperature to the controller where it is compared with the set temperature. When the correct temperature is reached, the heater is switched off. If the temperature falls, the heater is switched back on. This type of control is called **ON – OFF control**

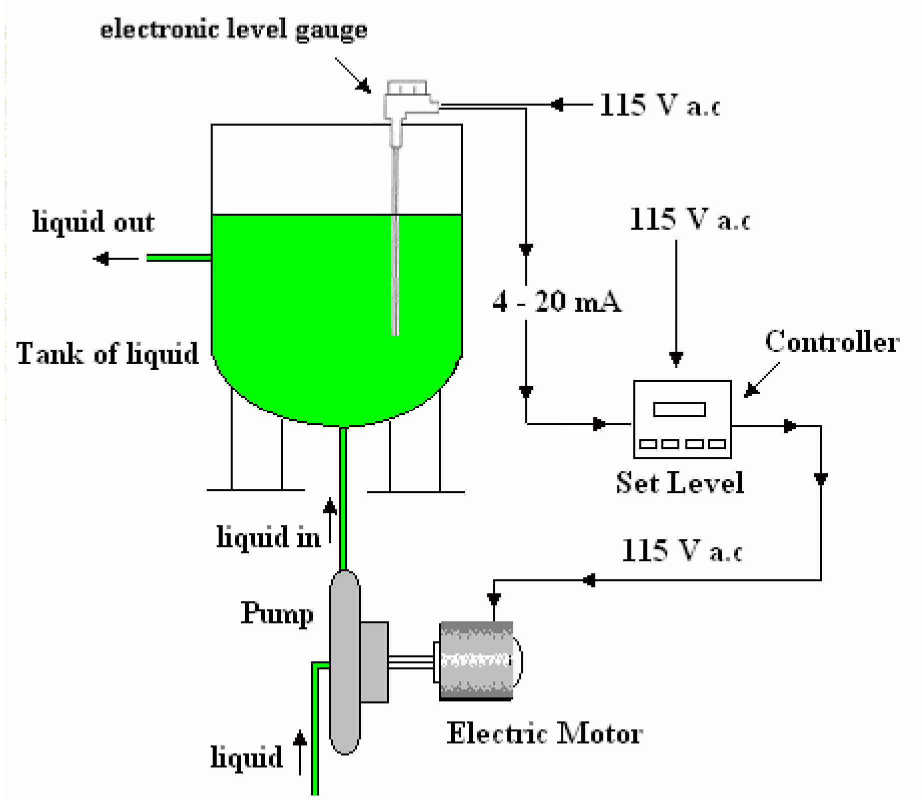


The block diagram shows how the closed loop is formed by the feedback path from the sensor.



SELF ASSESSMENT EXERCISE No. 5

The diagram shows how the level in a tank of liquid is maintained. Liquid is drawn off at various rates but the level must be maintained by pumping more in. The level is sensed by a level gauge that produces a signal of 4 – 20 mA to represent the level. This is connected to a controller that compares the actual level to that set on the controller. If the level is too low, the electric motor and the pump speed up to increase the inflow. If the level is too high, the motor slows down.



Draw a block diagram of the system. Identify and label all the inputs and outputs. Identify the feedback path that makes it a closed loop.