IPCD LECTURE NOTES

MODULE 2 , 3 & 4

EE EEE 5TH <u>SEM</u>

Digital signal conditioning

Review of Digital Fundamentals

- **Digital Information**
- The use of digital techniques in process control requires that process variable measurements and control information be encoded into a digital form.
- Digital signals themselves are simply two-state (binary) levels. These levels may be represented in many ways.
- The individual digital levels are referred to as *bits* of the word. Thus, for example, a 6-bit word consists of six independent digital levels, such as 110110 which can be thought of as a six-digit base 2 number.

Review of Digital Fundamentals

- **Decimal Whole Numbers** One of the most common schemes for encoding analog data into a digital word is to use the straight counting of decimal (or base 10) and binary number representations.
- **Octal and Hex Numbers** It is cumbersome for humans to work with digital words expressed as numbers in the binary representation. For this reason, it has become common to use either the octal (base 8) or hexadecimal (base 16, called hex) representations.
- **Fractional Binary Numbers:** Although not as commonly used, it is possible to define a fractional binary number in the same manner as whole numbers, using only the **1** and **0** of this counting system.

Review of Digital Fundamentals

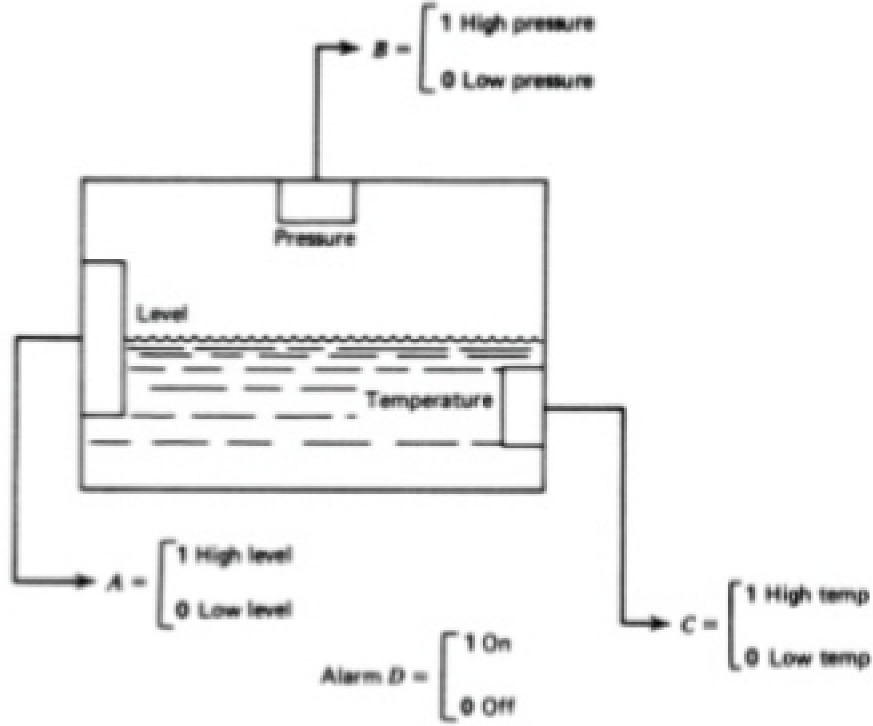
- Such numbers, just as in the decimal framework, represent divisions of the counting system to values less than unity.
- **Boolean Algebra:**
- Let us consider a simple example of how a Boolean equation may result from a practical problem
- The alarm will be triggered when the Boolean variable *D* goes to the logic true state. The alarm conditions are
- 1. Low level with high pressure
- 2. High level with high temperature
- 3. High level with low temperature and high pressure

Review of Digital Fundamentals

- We now define a Boolean expression with AND operations that will give a D=1 for each condition:

1. Low level with high pressure
2. High level with high temperature
3. High level with low temperature and high pressure

1. $D = \overline{A} \cdot B$ will give $D = 1$ for condition 1.
2. $D = A \cdot C$ will give $D = 1$ for condition 2.
3. $D = A \cdot \overline{C} \cdot B$ will give $D = 1$ for condition 3.



Review of Digital Fundamentals

- The final logic equation results from combining all three conditions so that if any is true, the alarm will sound D=1 . This is accomplished with the OR operation

$$D = \overline{A} \cdot B + A \cdot C + A \cdot \overline{C} \cdot B$$

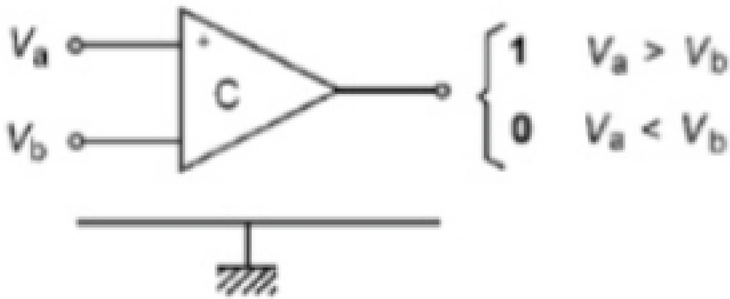
- This equation would now form the starting point for a design of electronic digital circuitry that would perform the indicated operations.

CONVERTERS

- The most important digital tool for the process-control technologist is one that translates digital information to analog and vice versa.
- Most measurements of process variables are performed by devices that translate information about the variable to an analog electrical signal.
- **Comparators:**
- The most elementary form of communication between the analog and digital is a device (usually an IC) called a *comparator*.

CONVERTERS

- This device, which is shown schematically in Figure , simply compares two analog voltages on its input terminals.
- Depending on which voltage is larger, the output will be a **1** (high) or a **0** (low) digital signal. The comparator is extensively used for alarm signals to computers or digital processing systems.



CONVERTERS

- **Digital-to-Analog Converters (DACs)**
- ADAC accepts digital information and transforms it into an analog voltage. The digital information is in the form of a binary number with some fixed number of digits.
- A unipolar DAC converts a digital word into an analog voltage by scaling the analog output to be zero when all bits are zero and some maximum value when all bits are one.
- This can be mathematically represented by treating the binary number that the word represents as a *fractional* number.

CONVERTERS

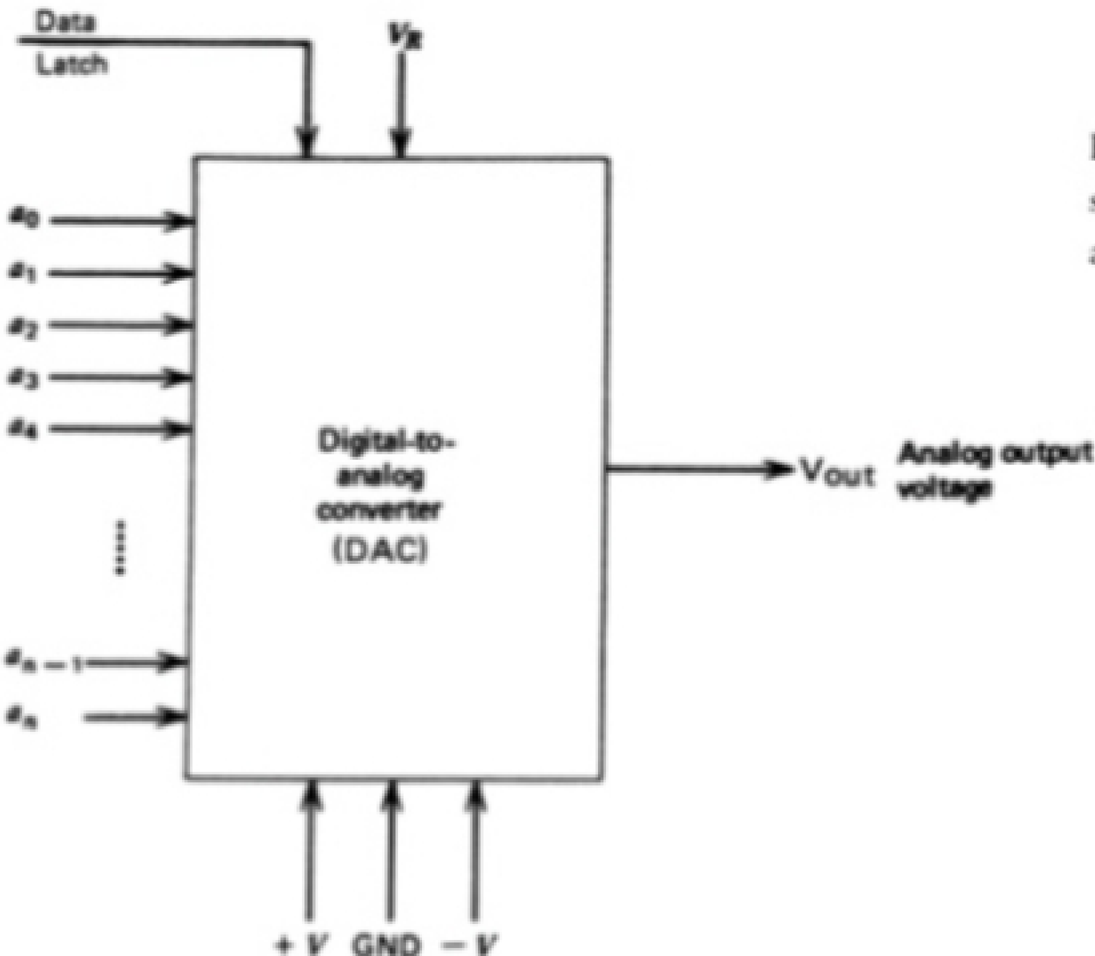


Fig: A generic DAC diagram, showing typical input and output signals

CONVERTERS

- **Analog-to-Digital Converters (ADCs)**
- Although there are sensors that provide a direct digital signal output and more are being developed, most still convert the measured variable into an analog electrical signal.
- With the growing use of digital logic and computers in process control, it is necessary to employ an ADC to provide a digitally encoded signal for the computer.
- The transfer function of the ADC can be expressed in a similar way to that of the DAC as given in Equation

$$b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n} \leq \frac{V_{in}}{V_R}$$

where $b_1 b_2 \ldots b_n$ = n-bit digital output
V_{in} = analog input voltage
V_R = analog reference voltage

The simplest operating mode for current mode temperature sensors is to load them with a precision resistor of 1% or better tolerance, and read the output voltage developed with either an ADC or a scaling amplifier/buffer. Figure 4-84 shows this technique with an ADC, as applicable to the AD592. The resistor load R1 converts the basic scaling of the sensor (1 µA/K) into a proportional voltage.

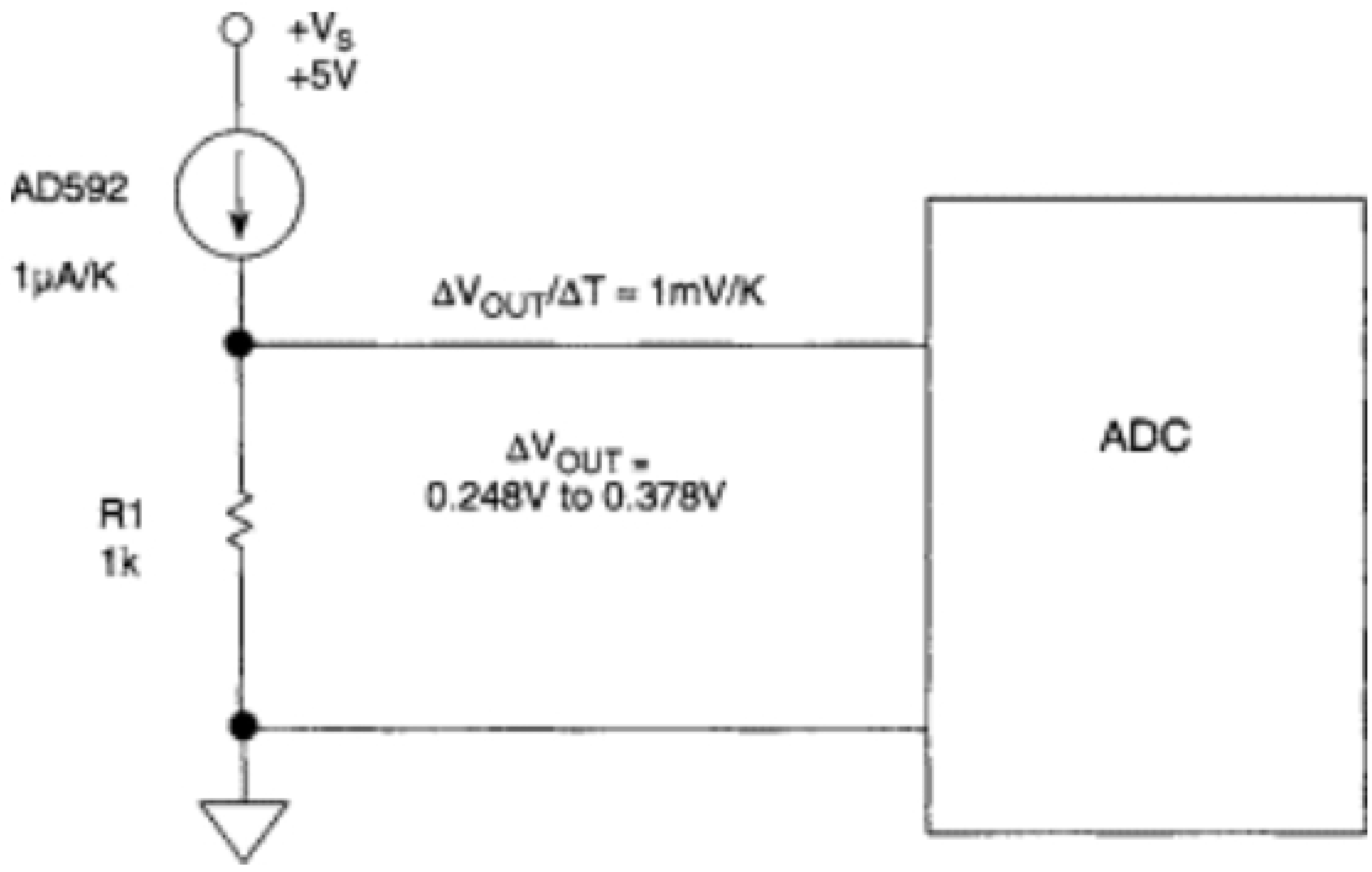


Figure 4-84. Current output temperature sensor driving a resistive load

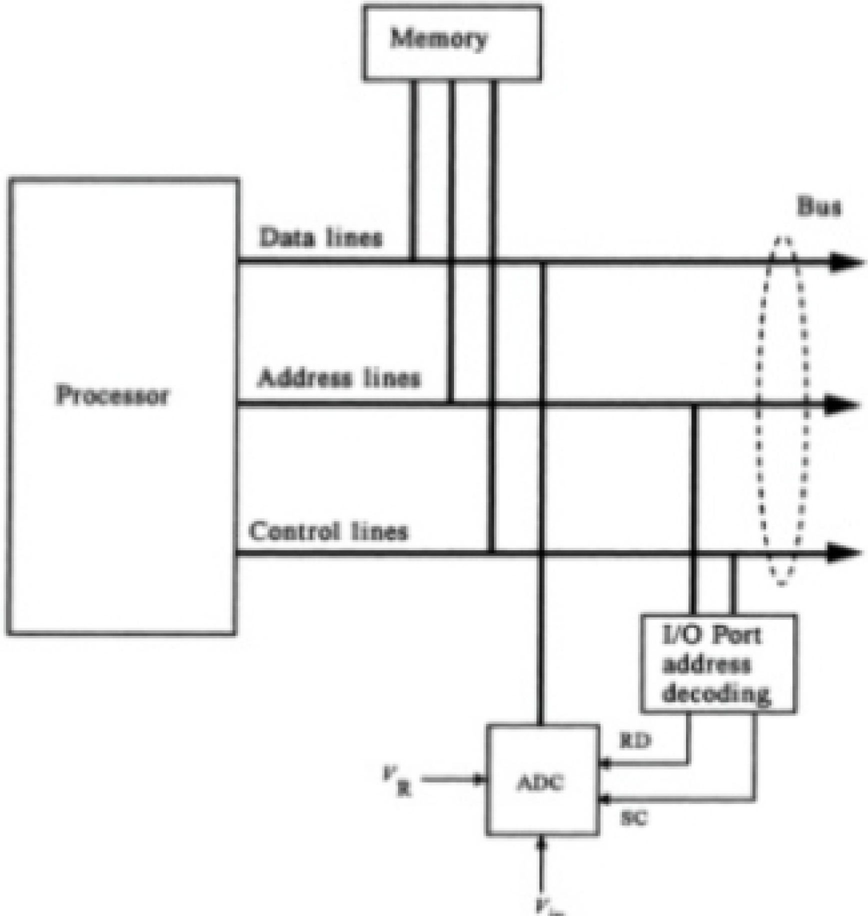
Choice of this resistor determines the overall sensitivity of the temperature sensor, in terms of V/K. For example, wit

DATA-ACQUISITION SYSTEMS

- Microprocessor-based personal computers (PCs) are used extensively to implement direct digital control in the process industries.
- These familiar desktop computers are designed much like the system shown in upcoming Figure 24, using a bus that consists of the data lines, address lines, and control lines.
- All communication with the processor is via these bus lines. This includes essential equipment such as RAM, ROM, disk, and CD-ROM.
- Special PCBs called data-acquisition systems (DASs) have been developed for the purpose of providing for input and output of analog data.

DATA-ACQUISITION SYSTEMS

- Fig: An ADC can be interfaced directly to the computer bus if it has tri-state outputs. Address decoding is required so the ADC can be operated by computer software.

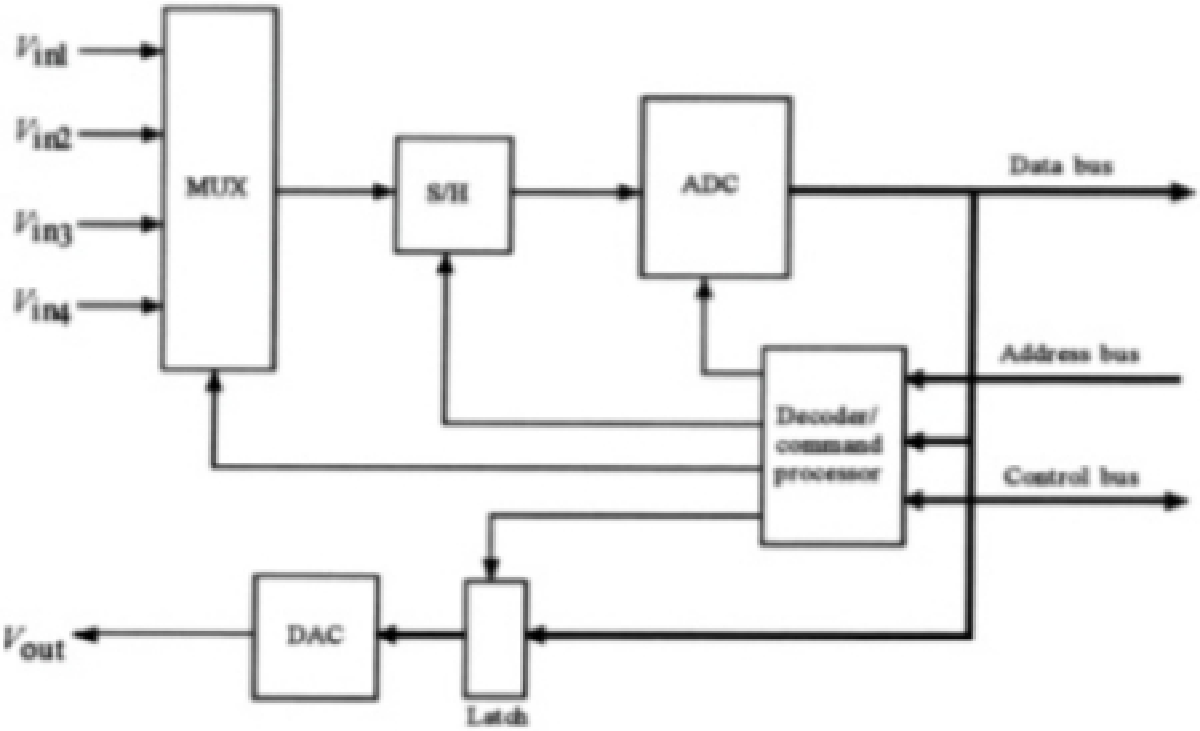


DATA-ACQUISITION SYSTEMS

- The PC also connects the bus lines to a number of printed circuit board (PCB) sockets, using an industry standard configuration of how the bus lines are connected to the socket. These sockets are referred to as *expansion slots*.
- **DAS Hardware**
- The hardware features of a general data-acquisition system are shown in upcoming Figure . Although there is variation from manufacturer to manufacturer, the system shown in this figure and described herein demonstrates the essential features of DASs.

DATA-ACQUISITION SYSTEMS

- Fig: Typical layout of a data-acquisition board for use in a personal computer expansion slot.



DATA-ACQUISITION SYSTEMS

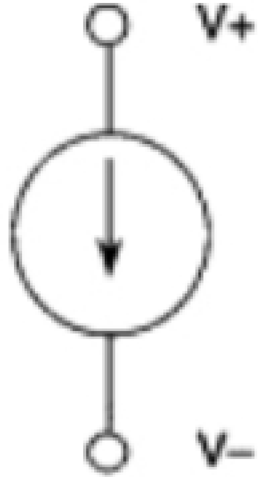
- **DAS Software**
- The process of selecting a channel and initiating a data input from that channel involves some interface between the computer and the DAS.
- This interface is facilitated by software that the computer executes. The software can be written by the user, but is often also provided by the DAS manufacturer in the form of programs on disk.
- Figure is a flowchart of the basic sequence of operations that must occur when a sample is required from the DAS.

Thermal Sensor

Thermal sensors built into the clothing provide a warning to fire-fighters of critical temperatures that will cause heat stress and burn.

Temperature sensors detect a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change. There are two basic types of temperature sensing:

- **Contact** temperature sensing requires the sensor to be in direct physical contact with the media or object being sensed. It can be used to monitor the temperature of solids, liquids or gases over an extremely wide temperature range.
- **Non-contact** measurement interprets the radiant energy of a heat source in the form of energy emitted in the infrared portion of the electromagnetic spectrum. This method can be used to monitor non-reflective solids and liquids but is not effective with gases due to their natural transparency.



AD592: TO-92 PACKAGE

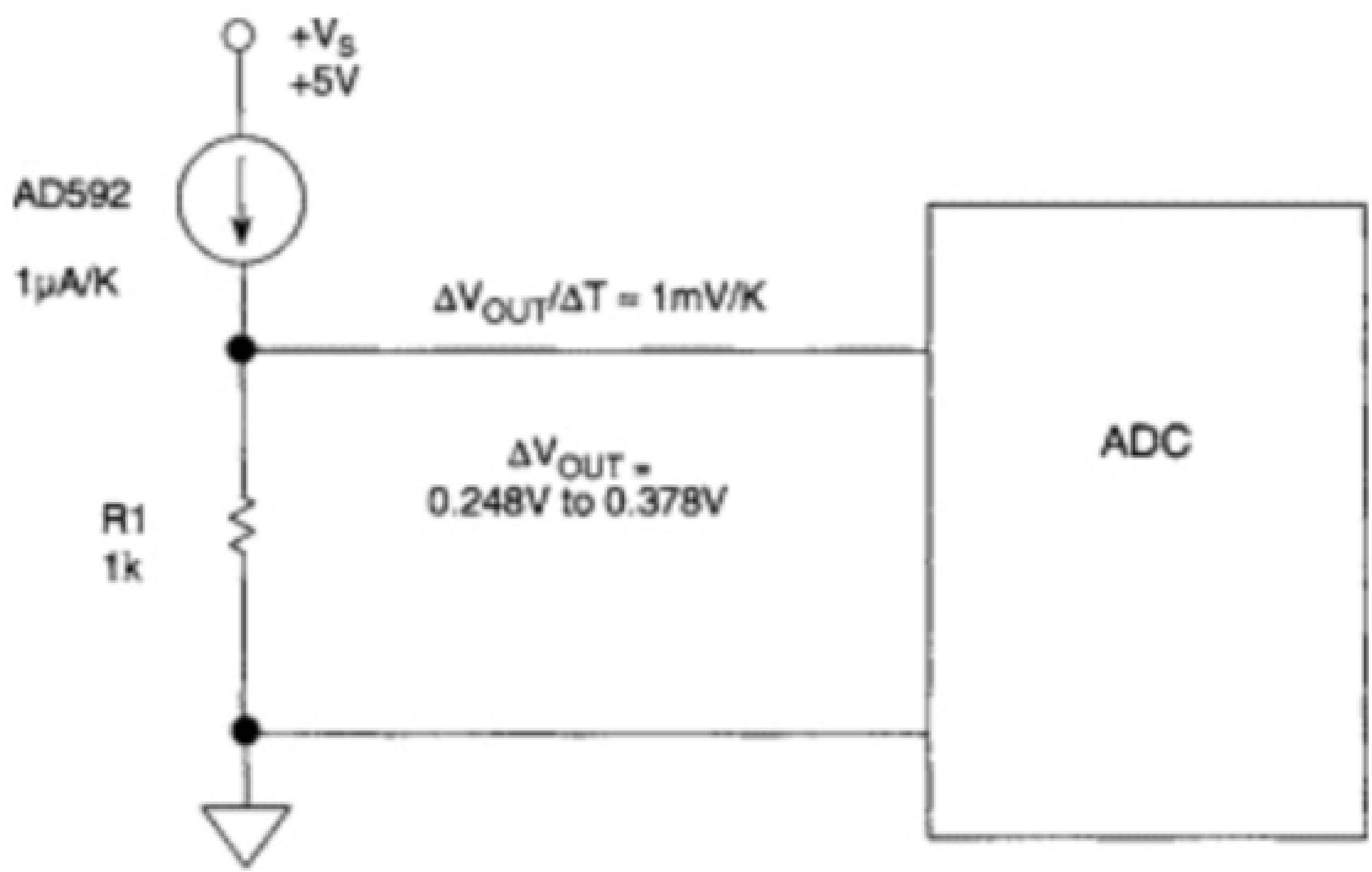
- 1µA/K Scale Factor
- Nominal Output Current @ 25°C: 298.2µA
- Operation from 4V to 30V
- ±0.5°C Max Error @ 25°C, ±1.0°C Error Over Temp, ±0.1°C Typical Nonlinearity (AD592CN)
- AD592 Specified from –25°C to +105°C

Current and Voltage Output Temperature Sensors

The concepts used in the bandgap voltage temperature sensor discussion above can also be used as the basis for a variety of IC temperature sensors, with linear, proportional-to-temperature outputs, of either current or voltage.

The AD592 device shown in Figure 4-83 is a two-terminal, current output sensor with a scale factor of 1 μA/K. This device does not require external calibration, and is available in several accuracy grades. The AD592 is a TO92 packaged version of the original AD590 TO52 metal packaged

The simplest operating mode for current mode temperature sensors is to load them with a precision resistor of 1% or better tolerance, and read the output voltage developed with either an ADC or a scaling amplifier/buffer. Figure 4-84 shows this technique with an ADC, as applicable to the AD592. The resistor load R1 converts the basic scaling of the sensor (1 μA/K) into a proportional voltage.



Temperature Coefficient Resistance

$$R = R_{ref}\,[1 + \alpha(T - T_{ref})]$$

Where,

R = Conductor resistance at temperature "T"

R_{ref} = Conductor resistance at reference temperature T_{ref}, usually 20°C, but sometimes 0°C.

α = Temperature coefficient of resistance for conductor material.

T = Conductor temperature in degrees Celcius.

T_{ref} = Reference temperature that α is specified at for the conductor material

The "alpha" (α) constant is known as the ***temperature coefficient of resistance*** and symbolizes the resistance change factor per degree of temperature change. Just as all materials have a certain specific resistance (at 20° C), they also *change* resistance according to temperature by certain amounts. For pure metals, this coefficient is a positive number, meaning that resistance *increases* with increasing temperature. For the elements carbon, silicon, and germanium, this coefficient is a negative number, meaning that resistance *decreases* with increasing temperature.

THERMISTOR?

A thermistor is a resistance thermometer, or a resistor whose resistance is dependent on temperature. The term is a combination of “thermal” and “resistor”. It is made of metallic oxides, pressed into a bead, disk, or cylindrical shape and then encapsulated with an impermeable material such as epoxy or glass.

There are two types of thermistors: Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). With an NTC thermistor, when the temperature increases, resistance decreases. Conversely, when temperature decreases, resistance increases. This type of thermistor is used the most.

HOW DOES THE THERMISTOR "READ" TEMPERATURE?

A thermistor does not actually "read" anything, instead the resistance of a thermistor changes with temperature. How much the resistance changes depends on the type of material used in the thermistor.

Unlike other sensors, thermistors are nonlinear, meaning the points on a graph representing the relationship between resistance and temperature will not form a straight line. The location of the line and how much it changes is determined by the construction of the thermistor. A typical thermistor graph looks like this:

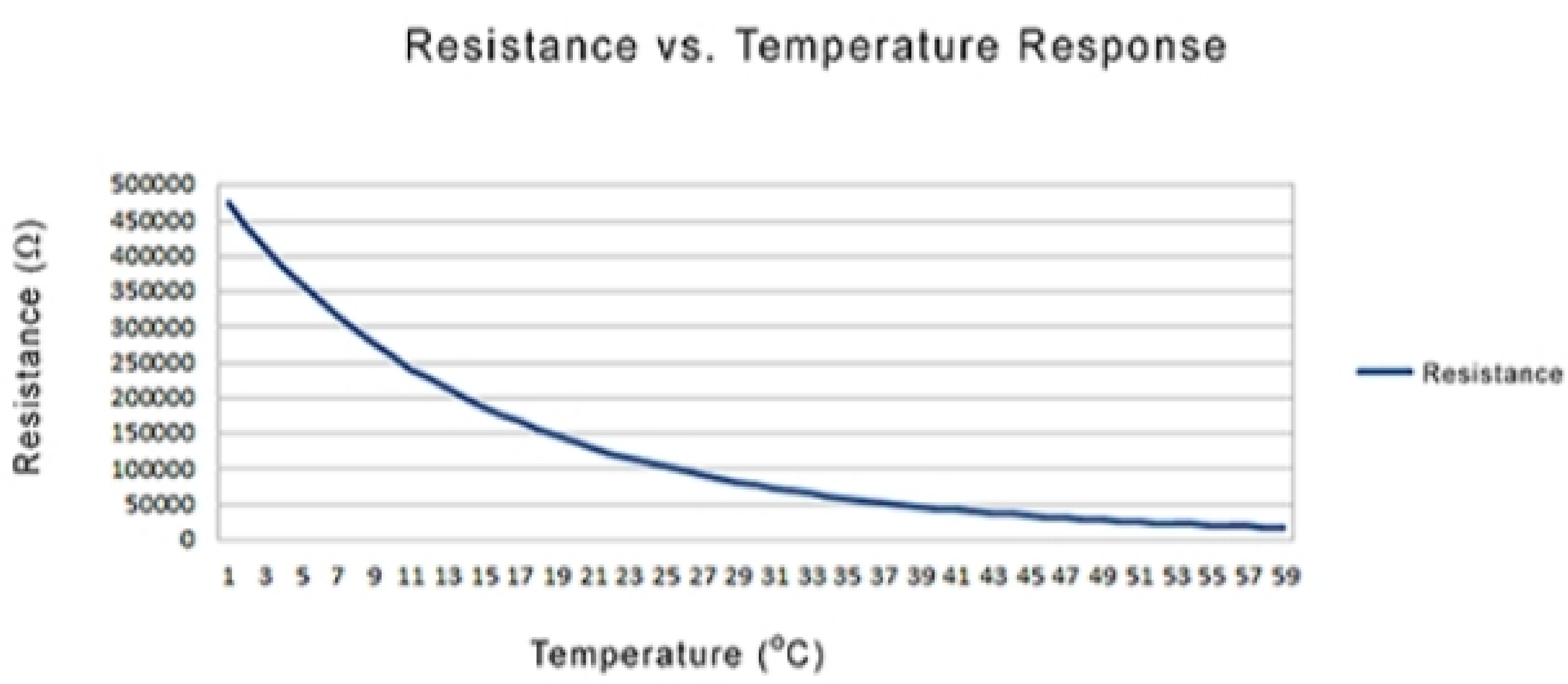


Figure 2: Resistance vs. Temperature

resistance decreases. Conversely, when temperature decreases, resistance increases. This type of thermistor is used the most.

A PTC thermistor works a little differently. When temperature increases, the resistance increases, and when temperature decreases, resistance decreases. This type of thermistor is generally used as a fuse.

Typically, a thermistor achieves high precision within a limited temperature range of about 50°C around the target temperature. This range is dependent on the base resistance.

The thermistor symbols are:

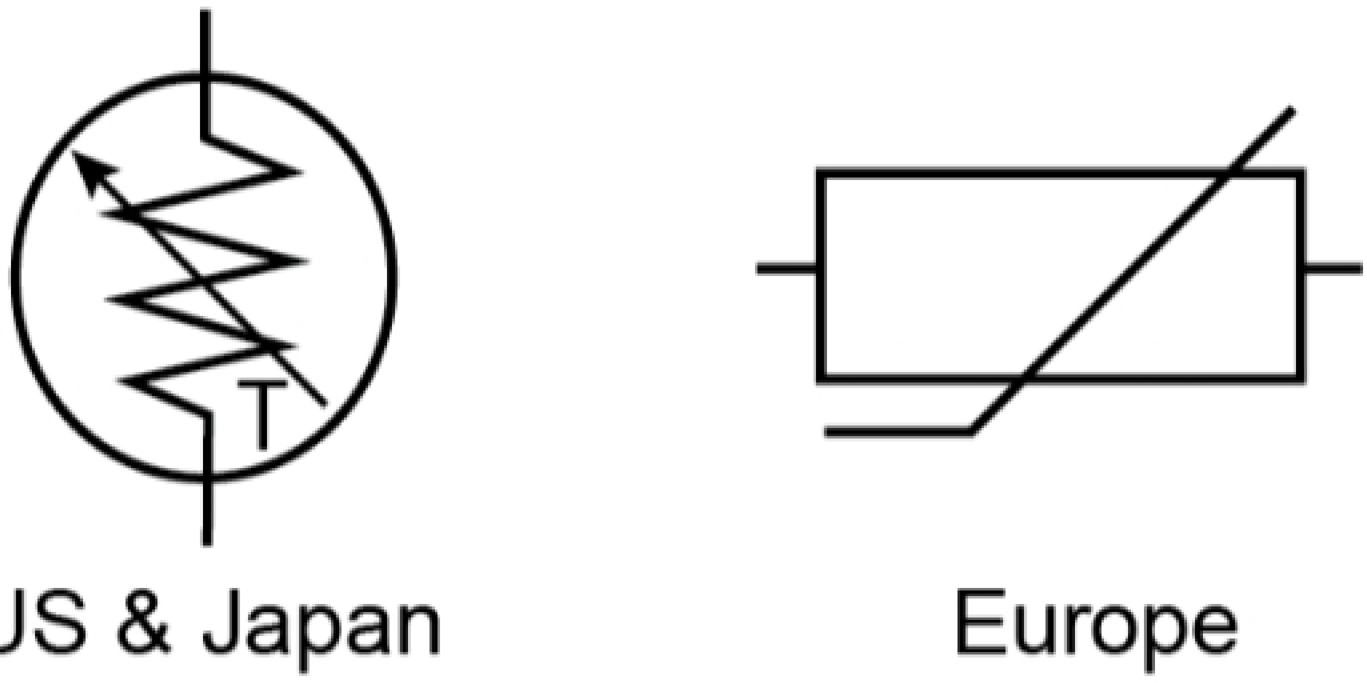


Figure 1: Thermistor Symbol — US and Japan

The arrow by the T signifies that the resistance is variable based on temperature. The direction of the arrow or bar is not significant.

Thermistors are easy to use, inexpensive, stu
respond predictably to changes in temperatur
they do not work well with excessively hot or co

Advantages

- Durable
- Long lasting
- Highly sensitive
- Small size
- Lowest cost
- Best for measuring single point temperature

- Best response time
- Linear output
- Widest operating temperature range
- Best for measuring a range of temperatures

- Moderately expensive
- Linear output

- Moderately expensive
- Linear output

Disadvantages

- Nonlinear output
- Limited temperature range
- Slow response time

- Expensive
- Low sensitivity

What is a Thermocouple?

A Thermocouple is a sensor used to measure temperature. Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where the temperature is measured. When the junction experiences a change in temperature, a voltage is created. The voltage can then be interpreted using thermocouple reference tables to calculate the temperature.

There are many types of thermocouples, each with its own unique characteristics in terms of temperature range, durability, vibration resistance, chemical resistance, and application compatibility. Type J, K, T, & E are "Base Metal" thermocouples, the most common types of thermocouples.Type R, S, and B thermocouples are "Noble Metal" thermocouples, which are used in high temperature applications (see thermocouple temperature ranges for details).

Thermocouples are used in many industrial, scientific, and OEM applications. They can be found in nearly all industrial markets: Power Generation, Oil/Gas, Pharmaceutical, BioTech, Cement, Paper & Pulp, etc. Thermocouples are also used in everyday appliances like stoves, furnaces, and toasters.

Thermocouples are typically selected because of their low cost, high temperature limits, wide temperature ranges, and durable nature.

❶ Type K Thermocouple (Nickel-Chromium / Nickel-Alumel): The type K is the most common type of thermocouple. It's inexpensive, accurate, reliable, and has a wide temperature range.

Temperature Range:

- Thermocouple grade wire, –454 to 2,300F (–270 to 1260C)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 2.2C or +/- .75%
- Special Limits of Error: +/- 1.1C or 0.4%

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❷ Type J Thermocouple (Iron/Constantan): The type J is also very common. It has a smaller temperature range and a shorter lifespan at higher temperatures than the Type K. It is equivalent to the Type K in terms of expense and reliability.

Temperature Range:

- Thermocouple grade wire, -346 to 1,400F (-210 to 760C)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 2.2C or +/- .75%
- Special Limits of Error: +/- 1.1C or 0.4%

---

❸ Type T Thermocouple (Copper/Constantan): The Type T is a very stable thermocouple and is often used in extremely low temperature applications such as cryogenics or ultra low freezers.

Temperature Range:

- Thermocouple grade wire, -454 to 700F (-270 to 370C)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 1.0C or +/- .75%
- Special Limits of Error: +/- 0.5C or 0.4%

---

❹ Type E Thermocouple (Nickel-Chromium/Constantan): The Type E has a stronger signal & higher accuracy than the Type K or Type J at moderate temperature ranges of 1,000F and lower. See temperature chart (linked) for details.

Mechanical sensors are used to measure variables such as position, velocity, acceleration, force, pressure, levels (such as a liquid in a tank), and flow. This section describes some sensors used by the pulp and paper industry; more information on these and other sensors is found in the a study by Johnson (1993), which is the source of much of the information in this section.

Electrical Position Sensors

Position sensors rely on a change of capacitance, resistance, inductance, or reluctance. The capacitance of a capacitor depends on the distance between two plates or on how two plates overlap. A potentiometric displacement sensor uses a wire of relatively high resistance with a wiper in electrical contact with the wire. As the

Electrical Position Sensors

Position sensors rely on a change of capacitance, resistance, inductance, or reluctance. The capacitance of a capacitor depends on the distance between two plates or on how two plates overlap. A potentiometric displacement sensor uses a wire of relatively high resistance with a wiper in electrical contact with the wire. As the object moves along the wire, the resistance of the circuit changes. By measuring the resistance, the position of the object along the wire is known. Variable inductance is achieved by the use of a ferromagnetic *core* in the shape of a rod that is surrounded by a hollow *coil* of wire. As the core enters the coil, the inductance of the coil is changed. With reluctance sensors, the magnetic flux coupling between two or more coils is varied by a ferromagnetic core. Reluctance sensors, a type of transformer, are the basis of the prevalent linear variable differential transformer (LVDT) shown in Fig. 24.2. The signal is easily conditioned to give a DC voltage that is linearly proportional to position over part of the range of motion of the core; the sensitivity can be on the order of 0.001 mm movement. It is possible to alter the design to measure the angular displacement as the core is rotated.

Other Position Sensors

Ultrasound can be used as a *position sensor* by measuring the time it takes for a pulse of ultrasound to "echo" back to the transmitter. It is similar in principle to a radar. This technique has been used on early "self-focusing" cameras, some consumer measuring devices used to measure room sizes in houses, and other ranging devices.

Strain Gauges and Load Cells

Strain is the change in length of a material caused by a stress (force) on the object. For example, tensile loads on a metal rod cause the metal rod to elongate, while at the same time the cross-sectional area decreases slightly. If the force is limited to the elastic range of the metal rod, the metal rod will return to its original shape when the tensile force is released. A compression force causes the metal bar to contract with a slight increase in cross-sectional area. Strain gauges use this phenomenon to measure strain by the change in resistance of a metal. As metal increases in length and decreases in cross-sectional area, its resistance will increase;

Pressure Sensors

Pressure is force per area. If a fluid is at rest, one refers to static pressure. If a fluid is in motion, one refers to dynamic pressure, which is a function of the motion of the fluid. The relationship between *gauge pressure* is the difference between *absolute pressure* and *atmospheric pressure*. For example, a flat tire on an automobile is said to have a (gauge) pressure of zero, but it actually has an absolute pressure of 14.7 psi. The pressure (p) exerted by a liquid is a function of the density of the liquid (ρ), the acceleration due to gravity (g), and the height of the liquid (h), $p = \rho g h$. Pressure can be measured by monitoring the movement of a bellows with an LVDT. Strain gauges can be mounted on diaphragms to measure pressure; this method has been miniaturized onto integrated circuits.

Pressure can be measured mechanically by using a *Bourdon tube*, a coiled tube that is partially flattened (the pressure version of the coiled bimetallic strip used to measure temperature).

Flow Sensors

Flow rates of materials moved on conveyors can be determined by weighing a portion of the conveyor (dividing by the length of the section that is weighed) and multiplying by the speed of the conveyor to give units of weight (or mass) per unit of time. This method can be approximated by using an LVDT to measure the sag of the belt. Flow rates in pipes are often measured indirectly by measuring the pressure (or head) that causes flow in a pipe. Flow in pipes can be measured by placing a restriction in the pipe and measuring the pressure drop (Bernoulli's principle) in the restriction. *Rotameters* use an obstruction in the flow path (a ball that rises in a tapered, vertical column); the flow provides the force to raise the ball against gravity. A vane that is pushed upward by the fluid is an indicator of fluid velocity if the vane's position is monitored.

Magnetic flow meters use an insulated portion of pipe where two coils (on the outside top and bottom of the pipe) generate a magnetic field.

Optical sensors for system monitoring and process cor

Electro-optical sensors are electronic detectors that convert light, or a change in light, into an electronic signal. These sensors are able to detect electromagnetic radiation from the infrared up to the ultraviolet wavelengths.[1] They are used in many industrial and consumer applications, for example:

- Lamps that turn on automatically in response to darkness
- Position sensors that activate when an object interrupts a light beam
- Flash detection, to synchronize one photographic flash to another
- Photoelectric sensors that detect the distance, absence, or presence of an object

Function

An optical sensor converts light rays into electronic signals. It measures the physical quantity of light and then translates it into a form that is readable by an instrument. An optical sensor is generally part of a larger system that integrates a source of light, a measuring device and the optical sensor. This is often connected to an electrical trigger. The trigger reacts to a change in the signal within the light sensor. An optical sensor can measure the changes from one or several light beams. When a change occurs, the light sensor operates as a photoelectric trigger and therefore either increases or decreases the electrical output. An optical switch enables signals in optical fibres or integrated optical circuits to be switched selectively from one circuit to another. An optical switch can operate by mechanical means or by electro-optic effects, magneto-optic effects as well as by other methods. Optical switches are optoelectronic devices which can be integrated with integrated or discrete microelectronic circuits.

Types of optical sensors and switches

There are many different kinds of optical sensors, the most common types are:[2]

- Photoconductive devices convert a change of incident light into a change of resistance.
- Photovoltaics, commonly known as solar cells, convert an amount of incident light into an output voltage.
- Photodiodes convert an amount of incident light into an output current.
- Phototransistors are a type of bipolar transistor where the base-collector junction is exposed to light. This results in the same behaviour of a photodiode, but with an internal gain.

Optical Switches are usually used in optical fibers, where the electro-optic effect is used to switch one circuit to another. These switches can be implemented with, for example, microelectromechanical systems or piezoelectric

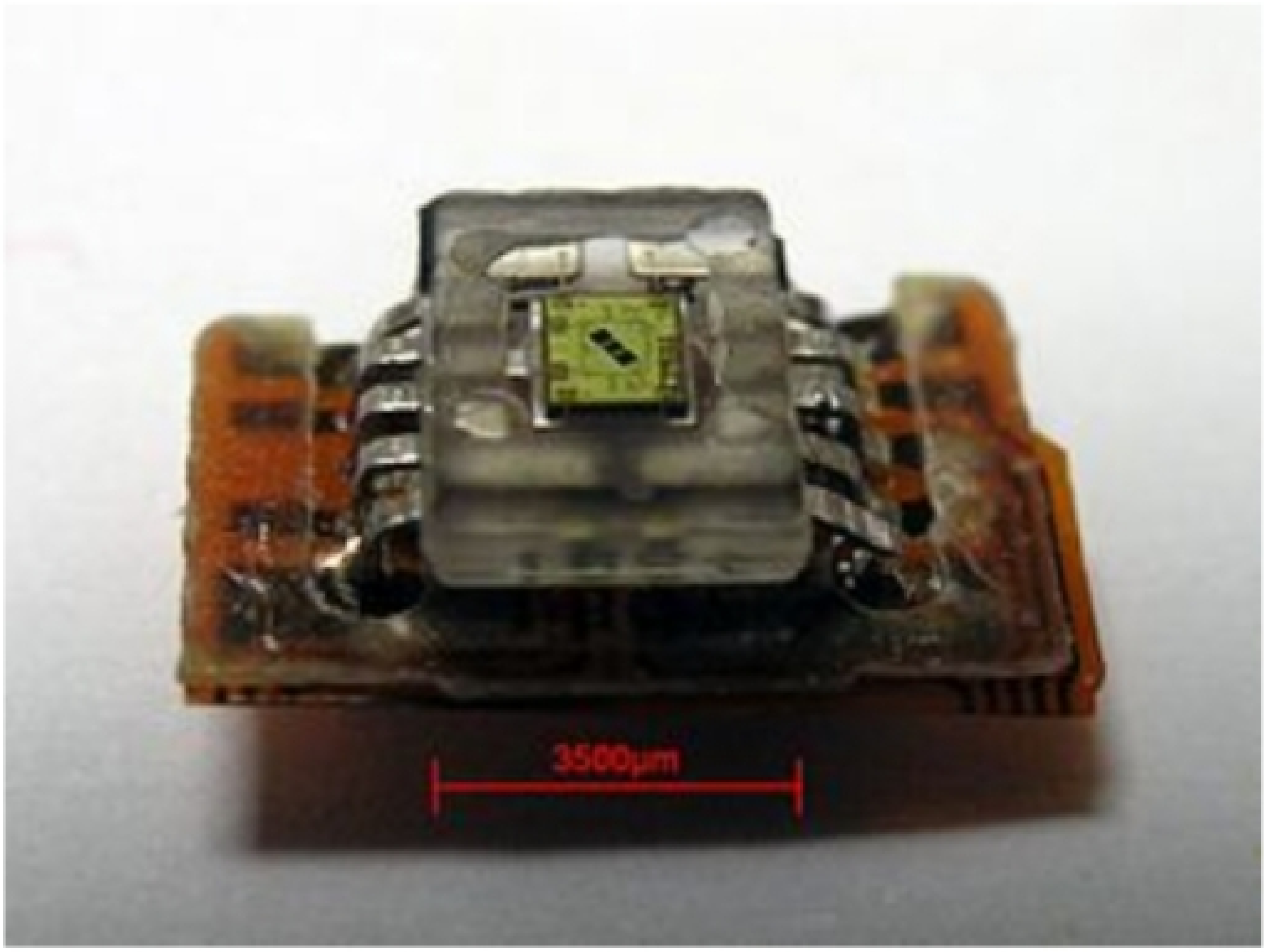
^ Applications

Optical heart-rate sensor

Electro-optical sensors are used whenever light needs to be converted to energy. Because of this, electro-optical sensors can be seen almost anywhere. Common applications are smartphones where sensors are used to adjust screen brightness, and smartwatches in which sensors are used to measure the wearer's heartbeat.

Optical sensors can be found in the energy field to monitor structures that generate, produce, distribute, and convert electrical power. The distributed and nonconductive nature of optical fibres makes optical sensors perfect for oil and gas applications, including pipeline monitoring. They can also be found in wind turbine blade monitoring, offshore platform

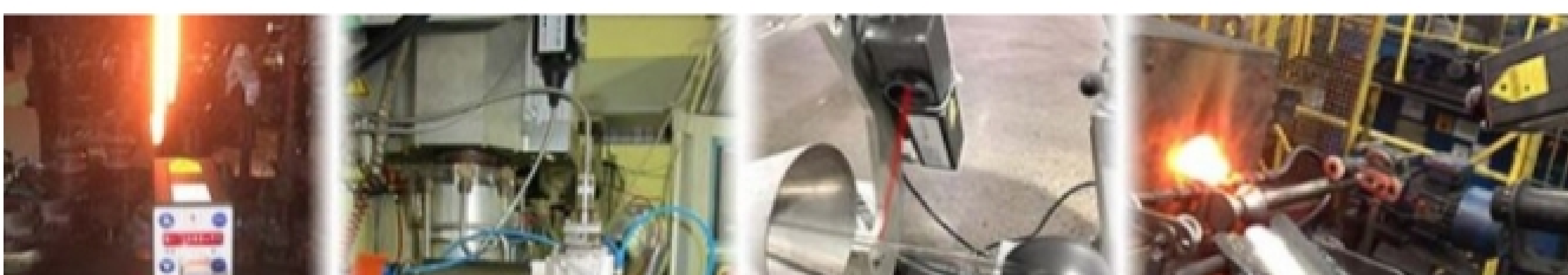
Photodetectors, also called **photosensors**, are sensors of light or other electromagnetic radiation. A photo detector has a p–n junction that converts light photons into current. The absorbed photons make electron–hole pairs in the depletion region. Photodiodes and photo transistors are a few examples of photo detectors. Solar cells convert some of the light energy absorbed into electrical energy.



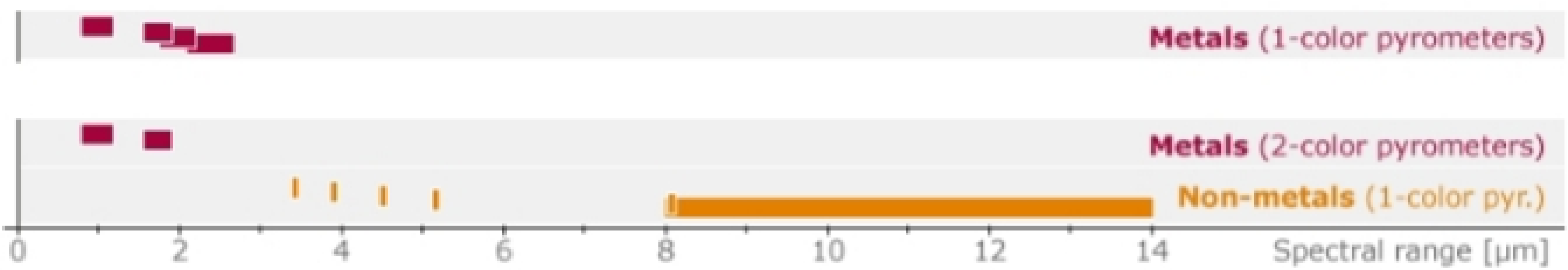
- Photoemission or photoelectric effect: Photons cause electrons to transition from the conduction band of a material to free electrons in a vacuum or gas.
- Thermal: Photons cause electrons to transition to mid-gap states then decay back to lower bands, inducing phonon generation and thus heat.
- Polarization: Photons induce changes in polarization states of suitable materials, which may lead to change in index of refraction or other polarization effects.
- Photochemical: Photons induce a chemical change in a material.

Infrared Pyrometers / Hot Metal Detectors

Pyrometers are **infrared thermometers** that optically measure surface temperatures at a (small) spot on a surface, and this quickly and very precisely thanks to digital signal processing. **Hot-metal detectors** are **infrared switches** and also detect the infrared radiation, but do not emit a temperature but a switching signal in case of temperature exceedance or undershot.



Pyrometers are available in different **spectral ranges**, the choice depends on the material to be measured. Thus, metals are measured in short-wave spectral ranges, non-metals usually in the long-wave.



The Metis M3 / H3 and Sirius series for stationary installation and the Capella C3 series for portable use measure in the short-wave range, the Metis series is available in different spectral ranges.

FINAL CONTROL ELEMENT

A final control element is defined as a mechanical device that physically changes a process in response to a change in the control system setpoint. Final control elements relevant to actuators include valves, dampers, fluid couplings, gates, and burner tilts to name a few. Final control elements are an essential part of process control systems, allowing an operator to achieve a desired process variable output by manipulating a process variable setpoint.

Current trends in industry focus on improving quality and efficiency in an effort to reduce process costs. Many industrial facilities are recognizing the bottom line savings found from improved process control performance through precise and consistent control of final control elements.

Traditional methods of positioning final control elements include electric actuators with squirrel-cage motors that suffer from duty-cycle limitations, poor resolution, and poor reliability. Commonly used pneumatic actuators suffer from stick/slip overshoot and high maintenance requirements. While it may seem like a given that your actuator should move when and where the controller tells it to, in many cases dead time and stick/slip overshoot cause delays in reaching the setpoint. The inefficiencies of these technologies can subject the process to relatively poor control and unplanned outages causing process variability and increased process costs. Many times these costs go unnoticed because they are not direct and immediately apparent. When selecting an actuator for a final control element, the actuator should have performance characteristics that will enable a control system to perform as designed.

The key final control element actuator performance characteristics are as follows:

- Precise, repeatable positioning typically better than 0.15% of span.
- The ability to start and stop instantaneously without dead time or position overshoot.
- Continuous duty rating without limitations on the number of starts per minute.
- Perform consistently and unaffected by load.
- Rugged industrial design capable of operating in difficult environments without an effect on performance.
- Minimal periodic maintenance required.

A final control element actuator designed with these characteristics provides two extremely important advantages:

1. An ability to follow the demand signal from the controller precisely and instantly. This ensures that the actuator responds exactly as directed by the controller. Thus, the actuator is not the limiting factor in the control loop and the controller can function to its optimal levels.
2. A high degree of maintenance-free reliability. An actuator designed to function as outlined above by default is more rugged than typical actuators. By design, then, it is capable of a much higher degree of reliability.

PROCESS CONTROL FOR VALVES

When it is necessary to improve process control performance, the first step is to improve final control element performance. Beck electric actuators provide the necessary control and reliability that is required for many final control elements. The Group 11 actuator product line is often found on low to medium torque applications (20 lb-ft to 5,200 lb-ft). Group 22 actuators are utilized for high torque applications (3,000 lb-ft to 8,000 lb-ft), and Group 31 compact rotary actuators are utilized on low torque applications (15 lb-ft to 30 lb-ft).

An **actuator** is a component of a machine that is responsible for moving and controlling a mechanism or system, for example by opening a valve. In simple terms, it is a "mover".

An actuator requires a control signal and a source of energy. The control signal is relatively low energy and may be electric voltage or current, pneumatic, or hydraulic fluid pressure, or even human power. Its main energy source may be an electric current, hydraulic pressure, or pneumatic pressure. When it receives a control signal, an actuator responds by converting the source's energy into mechanical motion. In the *electric*, *hydraulic*, and *pneumatic* sense, it is a form of automation or automatic control.

The hydraulic actuator consists of cylinder or fluid motor that uses hydraulic power to facilitate mechanical operation. The mechanical motion gives an output in terms of linear, rotatory or oscillatory motion. As liquids are nearly impossible to compress, a hydraulic actuator can exert a large force. The drawback of this approach is its limited acceleration.

The hydraulic cylinder consists of a hollow cylindrical tube along which a piston can slide. The term *single acting* is used when the fluid pressure is applied to just one side of the piston. The piston can move in only one direction, a spring being frequently used to give the piston a return stroke. The term *double acting* is used when pressure is applied on each side of the piston; any difference in force between the two sides

Pneumatic actuators enable considerable forces to be produced from relatively small pressure changes. Pneumatic energy is desirable for main engine controls because it can quickly respond in starting and stopping as the power source does not need to be stored in reserve for operation. Moreover, pneumatic actuators are cheaper, and often more powerful than other actuators. These forces are often used with valves to move diaphragms to affect the

The advantage of pneumatic actuators consists exactly in the high level of force available in a relatively small volume. While the main drawback of the technology consists in the need for a compressed air network composed of several components such as compressors, reservoirs, filters, dryers, air treatment subsystems, valves, tubes, etc. which makes the technology energy inefficient with energy losses that can sum up to 95%

Electromechanical Actuator

It converts the rotational force of an electric rotary motor into a linear movement to generate the requested linear movement through a mechanism either a belt (Belt Drive axis with stepper or servo) or a screw (either a ball or a lead screw or planetary mechanics)

The main advantages of electromechanical actuators are their relatively good level of accuracy respect to pneumatics, their possible long lifecycle and the little maintenance effort required (might require grease). It is possible to reach relatively high force, until order of 100 kN.

The main limitation of these actuators are the reachable speed, the important dimensions and weight they require.

Electrohydraulic Actuator

Another approach is an electrohydraulic actuator, where the electric motor remains the prime mover but provides torque to operate a hydraulic accumulator that is then used to transmit actuation force in much the same way that diesel engine/hydraulics are typically used in heavy equipment.

8: Discrete-State Process Control

Definitions

The *discrete state* of the process at any moment is the set of all input and output values.

An *event* in the system is defined by a particular state of the system, i.e. particular values of inputs and outputs.

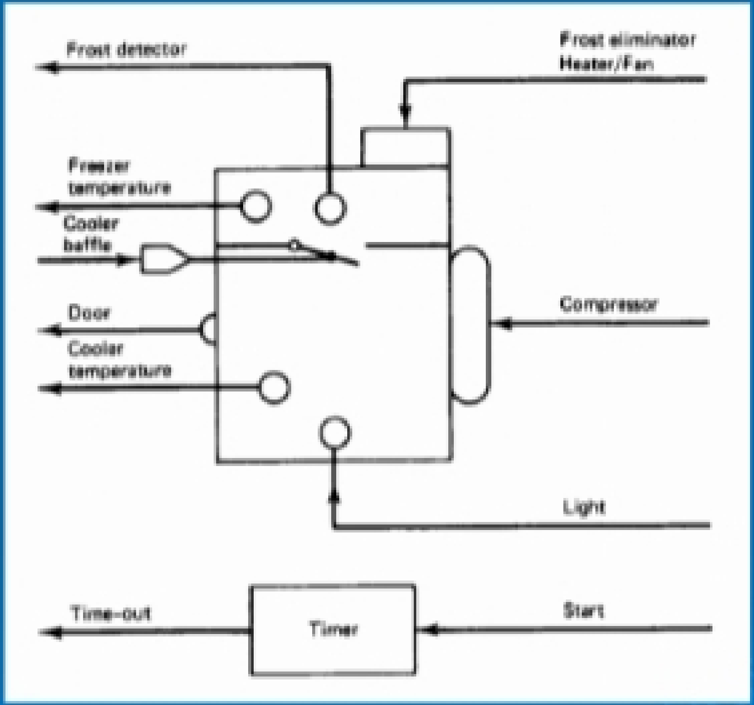
A *discrete-state process control* is a particular *sequence of events* through which the process accomplishes some objective

Example

Frost-free refrigerator/freezer

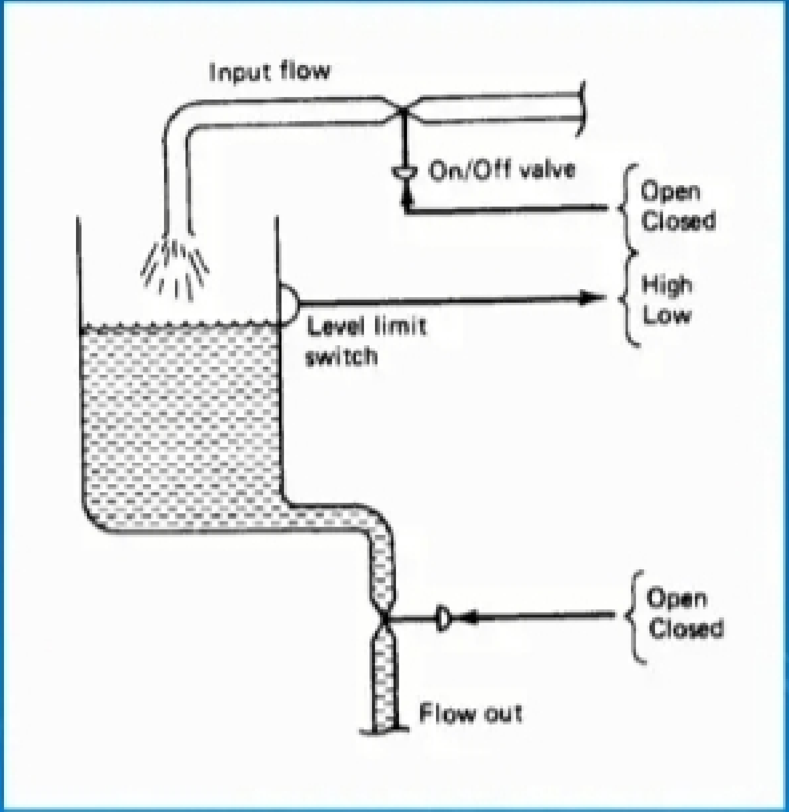
Discrete-state O/P

- Light on/off
- Compressor on/off
- Timer on/off
- Heater on/off
- Baffle open/closed



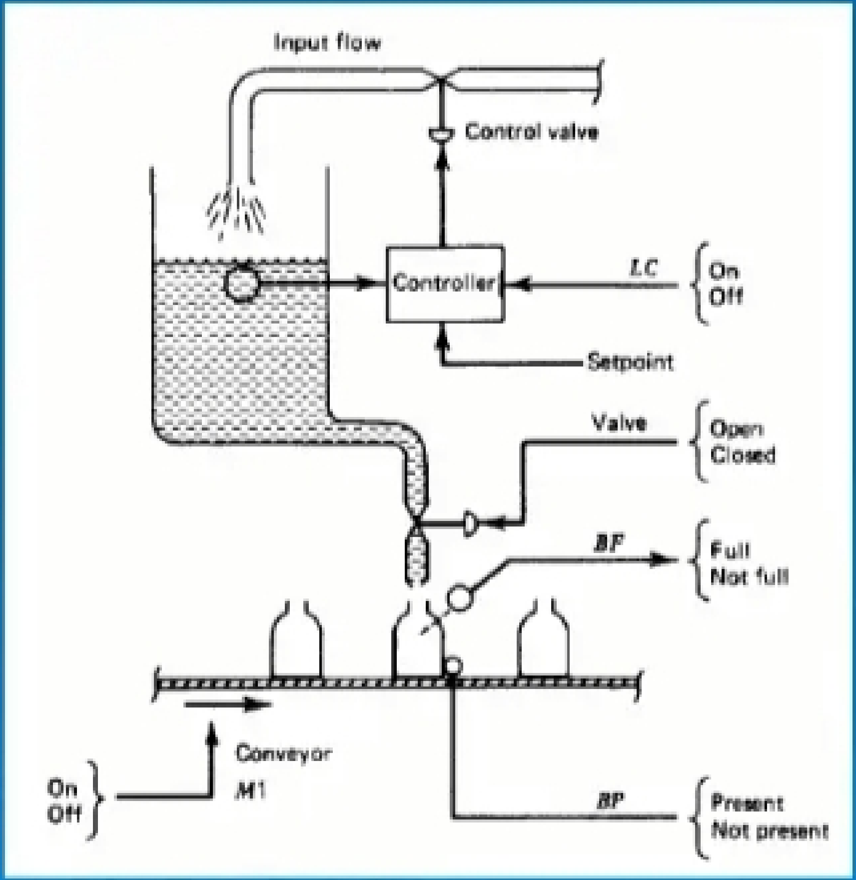
Discrete-State Variables

- Continuous Control
- Discrete Control



Discrete-State Variables

- Continuous Control
- Discrete Control
- Composite Discrete/Continuous Control

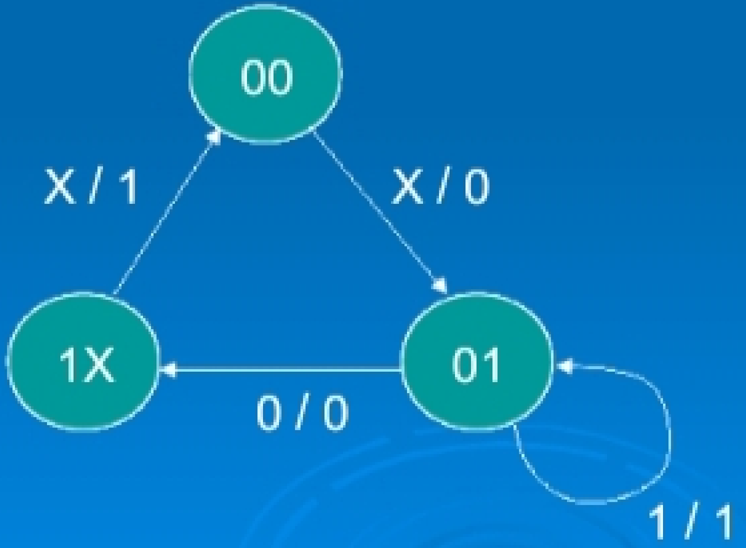


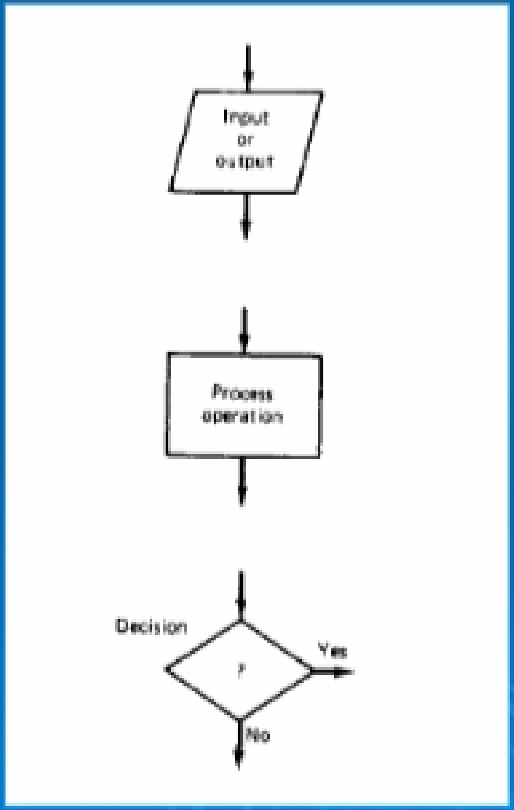
Process Specifications

- Process Objectives
- Process Hardware
  - Input Devices
    - Limit Switches
    - Comparators
    - Push Buttons
  - Output Devices
    - Lights
    - Motors
    - Solenoids

Event Sequence Description

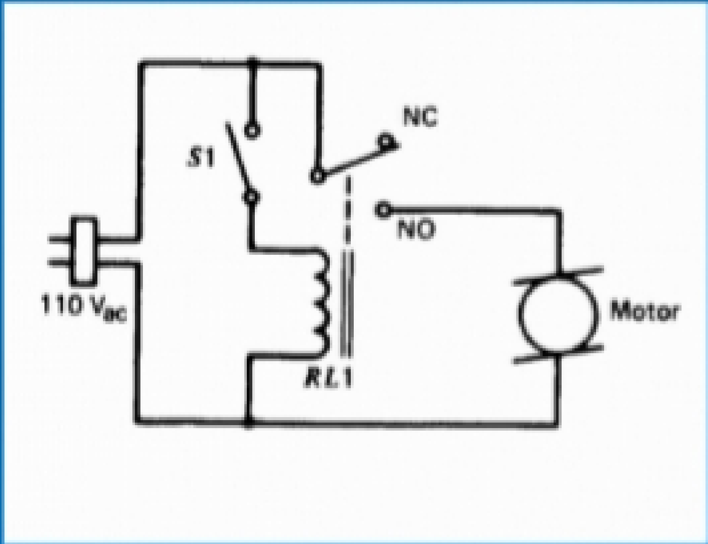
- Narrative Statements
- Flowcharts
- Binary-State

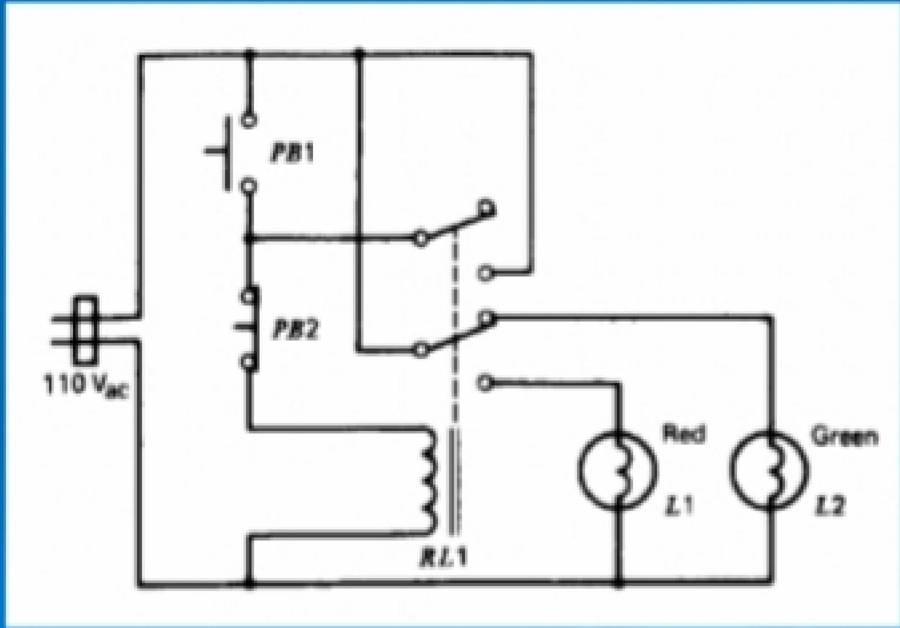




Relay Controllers & Ladder Diagrams

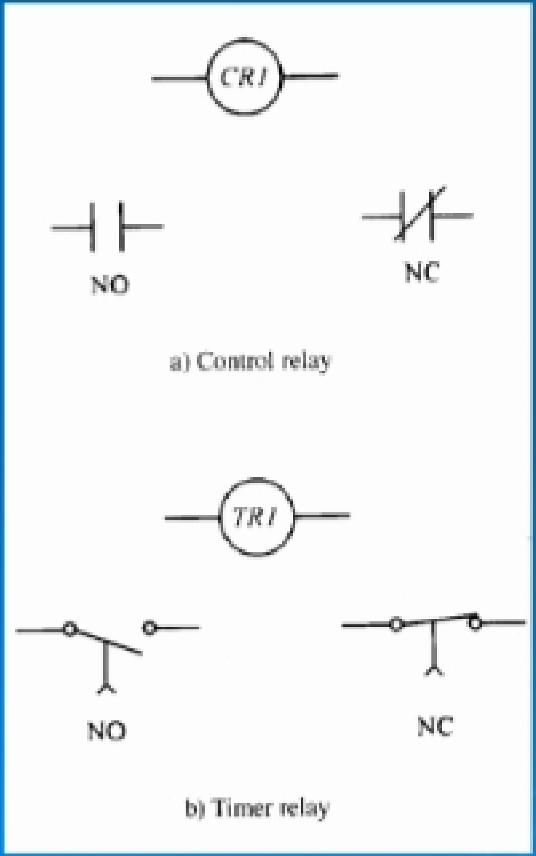
- Control Relays (Relay Sequencer)

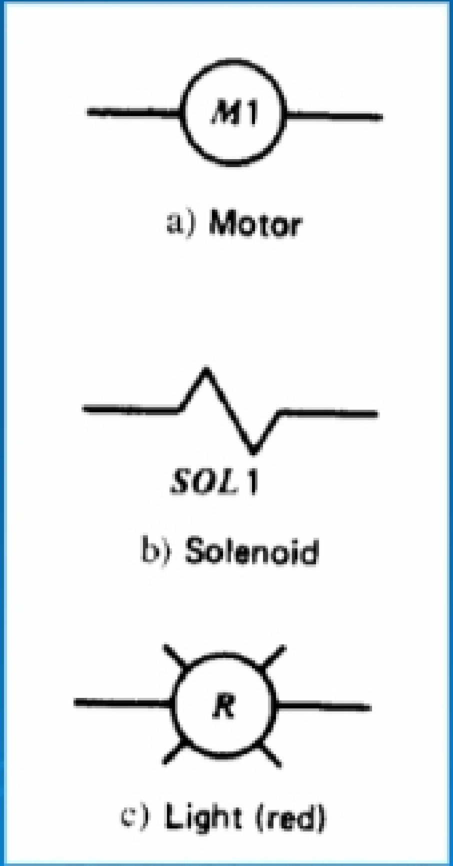


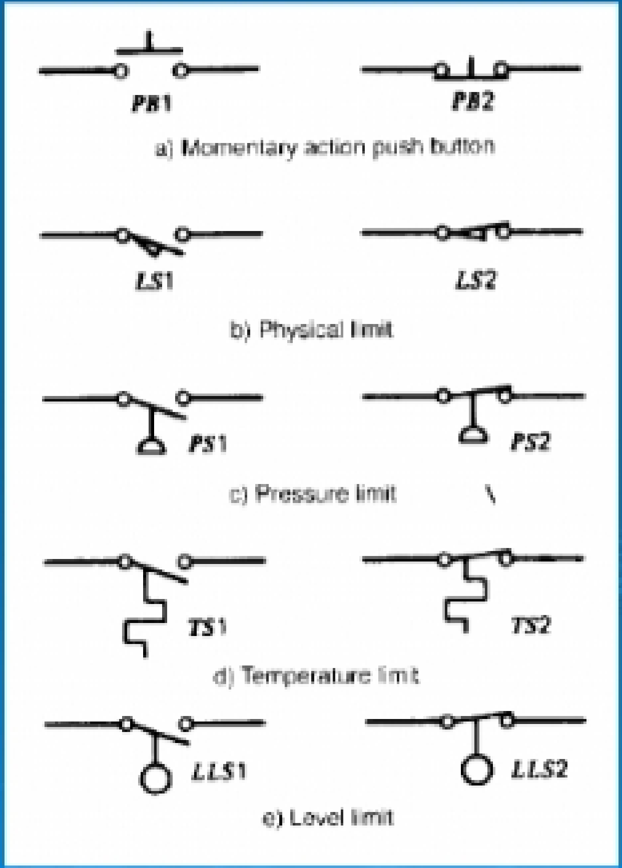


Relay Controllers & Ladder Diagrams

- Ladder Diagram

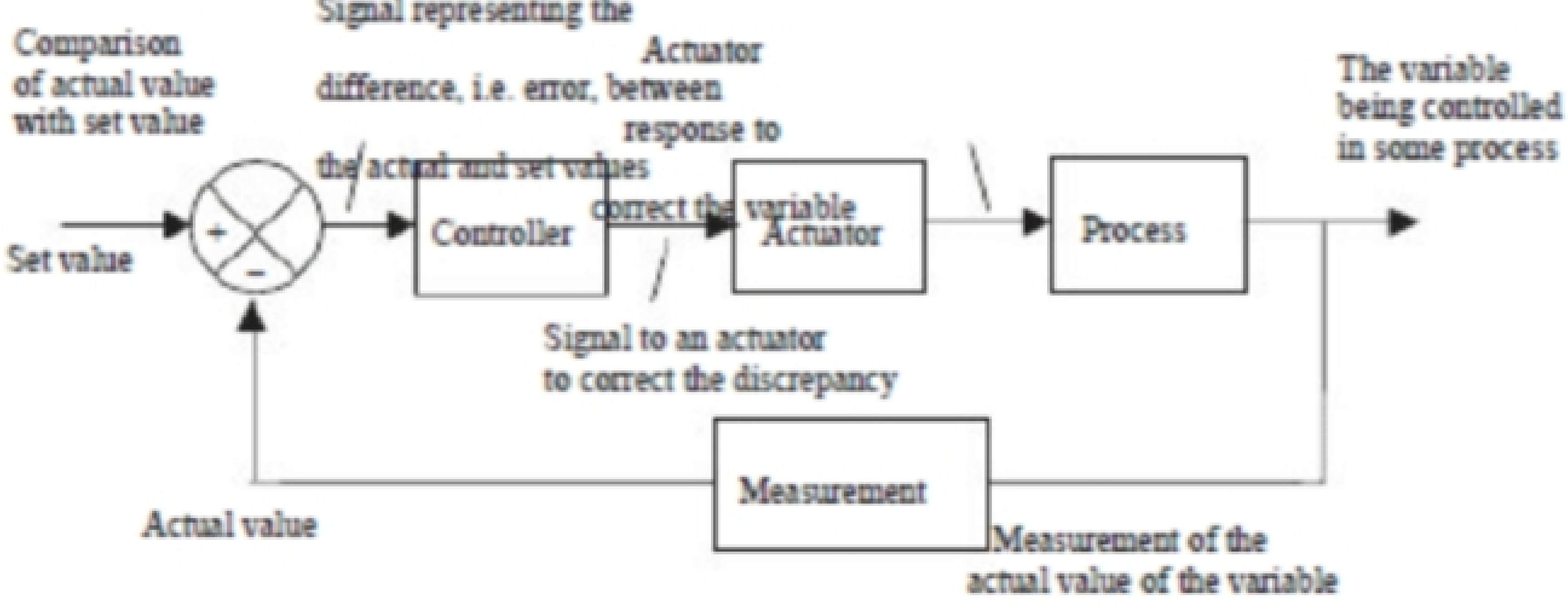






CLOSED LOOP CONTROL - PROGRAMMABLE LOGIC CONTROLLERS

You can control the temperature of a room by switching on an electric fire. The fire will heat the room up to the maximum temperature that is possible, bearing in mind the rateat which the fire heats the room and the rate at which it loses heat. This is termed open loop control in that there is no feedback to the fire to modify the rate at which it is heating the room. To control the temperature with feedback, you need a thermostat that can be set to switch the fire on when the room temperature is below the required value and switch it off when it goes above it. There is feedback of temperature information in this system; as such it is termed closed loop control.



Closed loop control.

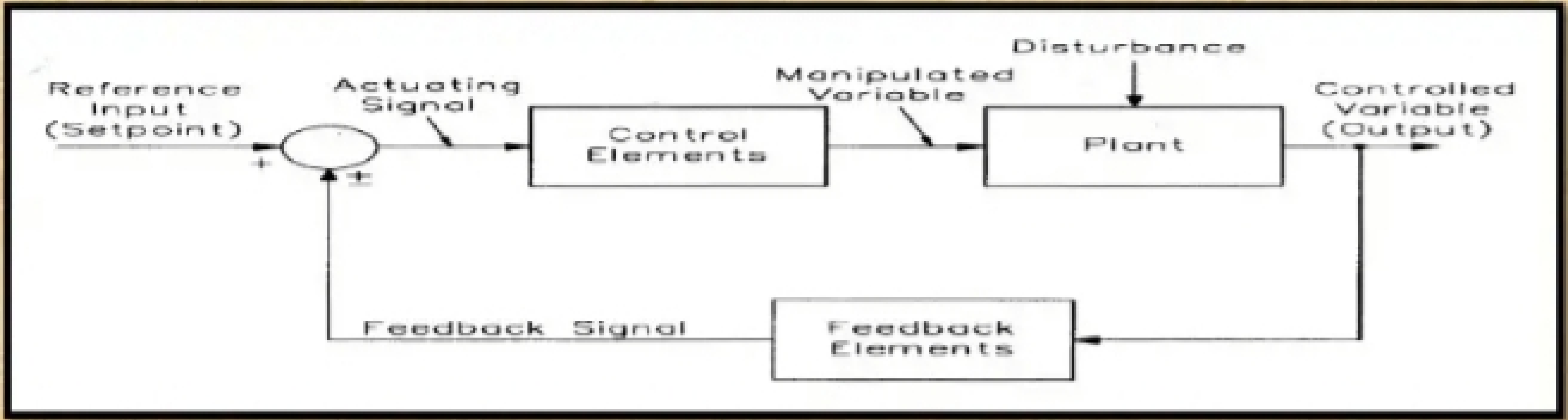
CONTROLLER PRINCIPLE

Concept control system

- To sense deviation of the output from the desired value and correct it, till the desired output is achieved
- Desired value of the output - reference output or set point

Controllers are the controlling element of a control loop

- element which accepts the error in some form and decided the proper corrective action
- Their function is to maintain a process variable (pressure, temperature, level..) at some desired value



Plant - system or process through which a particular quantity or condition is controlled. This is also called the *controlled system.*

Controller - control elements are components needed to generate the appropriate control signal applied to the plant

Feedback elements - components needed to identify the functional relationship between the feedback signal and the controlled output.

Reference point - external signal applied to the summing point of the control system to cause the plant to produce a specified action. This signal represents the desired value of a controlled variable and it also called "set point."

Controlled output - quantity or condition of the plant which is controlled. This signal represents the controlled variable.

Feedback signal - function of the output signal. It is send to the summing point and algebraically added to the reference input signal to obtain the actuating signal.

Actuating signal - the control action of he control loop and is equal to the algebraic sum of th reference input signal and feedback signal. This is also called the "error signal."

Manipulated variable - process acted upon to maintain the plant output(controlled variable) at the desired value.

Disturbance - undesirable input signal that upset the value of the controlled output of the plant.

Classification of Controllers

- Continuous modes

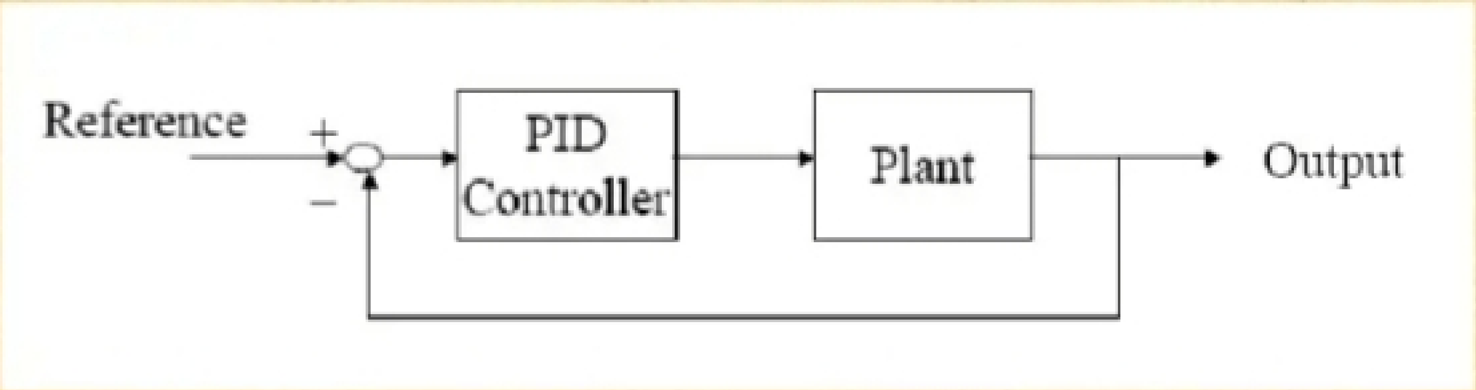
Four modes of control commonly used for most applications are:

Proportional (P)
Proportional plus Reset (PI)
Proportional plus Rate (PD)
Proportional plus Reset plus Rate (PID)

PID Controllers

- A particular control structure that has become almost universally used in industrial control.
- It is based on a particular fixed structure controller family, the so-called PID controller family.
- These controllers have proven to be robust and extremely beneficial in the control of many important applications.
- PID stands for:
  - **P** (*Proportional*)
  - **I** (*Integral*)
  - **D** (*Derivative*)

General Control System Arrangement



Modes of Controllers

- The mode of control is the manner in which a control system makes corrections relative to an error that exists between the desired value (set point) of a controlled variable and its actual value.
- The mode of control used for a specific application depends on the characteristics of the process being controlled. For example, some processes can be operated over a wide band, while others must be maintained very close to the set point.
- ***Deviation*** is the difference between the set point of a process variable and its actual value. This is a key term used when discussing various modes of control.

Four Modes of Controllers

- Four modes of control commonly used for most applications are:
  - Proportional (P)
  - Proportional plus Reset (PI)
  - Proportional plus Rate (PD)
  - Proportional plus Reset plus Rate (PID)

Modes of Controller Operation

In this chapter the different modes of controller operation are discussed. In any control system, where the dynamic variable has to be maintained at the desired set point value, it is the controller alone which enables to meet the requirements of control objective. The controller inputs the result of a measurement of the controlled or dynamic variable and determines an appropriate output to the final control element.

Usually final control elements understand certain range of signal transmission only. Hence the o/p of a controller must be translated to the range of possible values of final control element. This range is called as *controller parameter range*.

In terms of analog signal transmission this range of controller output is 4–20 mA. standard signal.

4 mA corresponds to 0% controller output i.e. minimum and 100% controller output i.e. maximum would be 20 MA respectively.

In discrete state process control systems, the output will range over all the states of the *n*-bit output. Generally, all 0's correspond to minimum output and all 1's represent maximum controller output. The controller output as percentage of full scale when the output varies between specified limits is given by the expression

$$\% P = \frac{\Delta p - P_{min}}{P_{max} - P_{min}} \times 100$$

where Δp = Actual controller output.

$P_{max}, P_{min} \Rightarrow$ Standard signal transmission range.

For example in 4–20 mA signal transmission, 4 mA corresponds to 0% controller 0/p and 20 mA, 100% controller 0/p. If we want to evaluate how much in terms of percentage would be 12 mA controller output, the above equation can be used.

Single speed floating control mode

In this mode the controller output changes at a fixed rate whenever the error exceeds the neutral zone. The analytic expression is

$$\frac{dp}{dt} = \pm K_F \quad |e| > \text{Neutral Zone}$$

where $\frac{dp}{dt}$ = rate of change of controller output,

K_F = Rate constant [%/sec]

The specific controller output is obtained by integrating the above equation.

$$P = \pm K_F t + P(0)$$

where $P(0)$ refers to initial setting of the controller when the error is zero. The characteristics of single speed floating controller mode is

Multiple speed floating controller mode

In single speed, the rate of change of controller output is fixed at cert of $\pm K_F$. In multiple speed control mode, there are several differen controller output depending on the nature of deviation or error.

The analytic expression can thus be modified as

$$\frac{dp}{dt} = \pm K_{Fi} \quad e > e_i$$

CONTINUOUS CONTROLLER MODES

e the discontinuous modes of operation, in continuous mod
h relation existing between controller output and error, whe
viation of the controlled variable from set point. The controll
nooth fashion to achieve the control objective.

2.4.1 Proportional Controller Mode

It is a natural extension of two position mode. In this mode there is a smooth relation between controller output and error before the output saturates at 0% [OFF state] or 100% [ON state]. Between these two saturation levels, there is a band of errors, where every value of error has a unique value of controller output i.e. there is a one-to-one correspondence existing betwee[illegible] output and error.

This range of errors to cover 0% to100% controller output is known as **"PROPORTIONAL BAND"**.

The analytic expression is written within this proportional band which describes the operation of proportional control action.

$$P = K_p e + P_0 \qquad \text{...(1)}$$

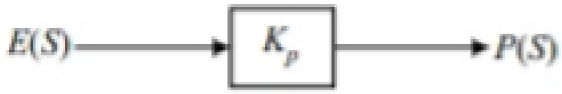
K_p = proportional gain,

P_0 = Initial value of controller o/p.

The transfer function representation is obtained by applying Laplace transform to equation (1),

$$P(s) = K_p . E(s) \text{ [Initial value is assumed to be zero]}$$

∴



CHARACTERISTICS OF PROPORTIONAL MODE

Figure (2.6) represents the characteristics of *P*-control action. The proportional band (*P.B*) is related to the gain of proportional controller K_p and is defined

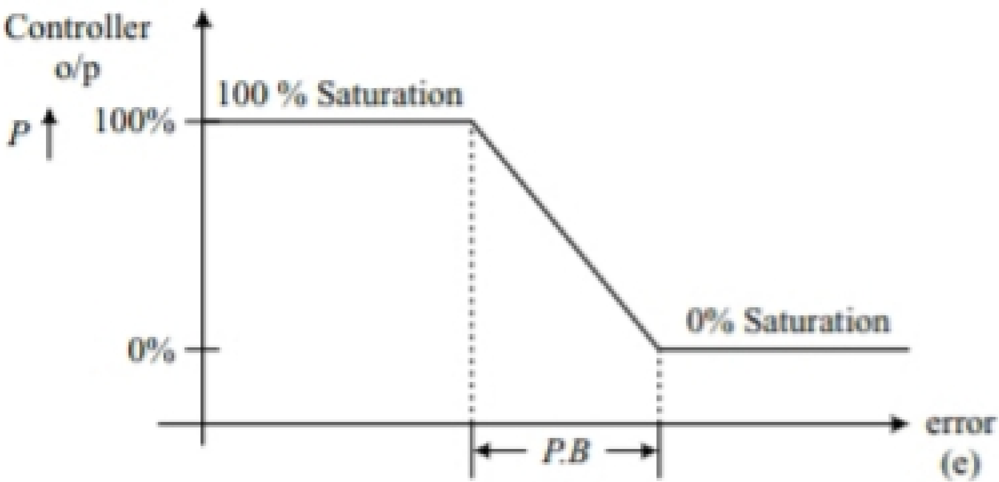
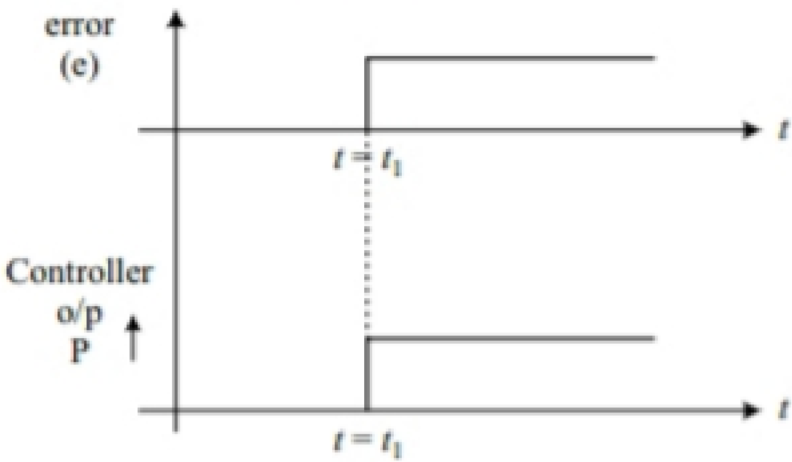


FIG. 2.6



2.4.2 Integral Controller Mode

This mode is an extension of floating control mode. Unlike the previous discontinuous mode, the rate of change of controller output is not constant at $\pm K_F$ but is directly proportional to error.

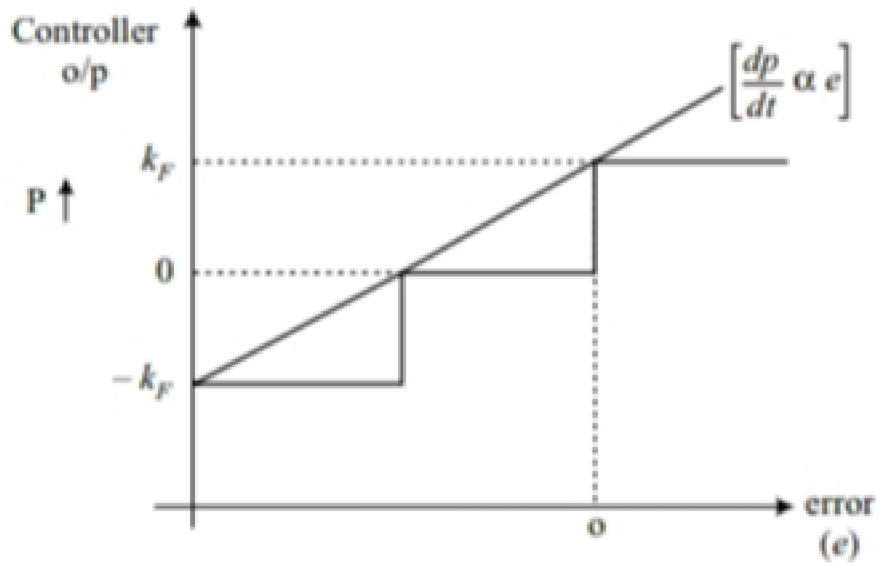


FIG. 2.9

The analytic expression may be written as

$$\frac{dp}{dt} \propto e$$

$$\frac{dp}{dt} = K_I \cdot e \qquad \text{...(4)}$$

where K_I = Integral scaling.

From equation (4), the rate of change of controller o/p is proportional to error. Thus when error occurs, the controller responds by sending an output at a rate that depends upon the size of the error and integral scaling K_I.

The analytic expression may be written as

$$\frac{dp}{dt} \propto e$$

$$\frac{dp}{dt} = K_I \cdot e$$

where K_I = Integral scaling.

A controller is a comparative device that receives an input signal from a measured process variable, compares this value with that of a predetermined control point value (set point), and determines the appropriate amount of output signal required by the final control element to provide corrective action within a control loop. **A Pneumatic Controller is a mechanical device designed to measure temperature or pressure and transmit a corrective air signal to the final control element.**

Principles of Operation

A Pneumatic Controller operates through a coordination of its thermal or pressure sensing system and its air signal relay system. The controller's sensing bulb or pressure connection, installed within the process application, senses change within the measured variable and relays this information (input signal) to the controller. The controller mechanically compares the signal against a predetermined set point and sends a corrective air signal to a pneumatic control valve, which modul process flow, thereby returning the application to desired condition.

Selecting a Pneumatic Controller

Control Function

Pneumatic Controllers can be specified for either on/off or proportional control. Processes which are characterized by stable load conditions can be controlled using on/off control with a **"quick-opening"** control valve, providing a full corrective response to a minimal change in the measured variable. Applications with unstable load conditions, or those requiring precise control, are best maintained using proportional control and an equal percentage valve trim design, which gives a corrective response that is proportionate to the change in the measured variable.

- **Proportional (P)** – Proportional control reacts to the size of the deviation from set point when sending a corrective signal. The size of the corrective signal can be adjusted in relation to the size of the error by changing the width of the proportional band. A narrow proportional band will cause a large corrective action in relation to a given amount of error, while a wider proportional band will cause a smaller corrective action in relation to the same amount of error.
- **On/Off (I/0)** – On/Off control recognizes only that a deviation exists. Any deviation between the set point and measured process variable will produce a full corrective signal.

Range and Set Point

Temperature ranges from -100°F through 600°F and pressure ranges from 30 psi through 1000 psi are available. The set point is the actual temperature or pressure required within the process. A set point indicator (adjusted via an external knob) and a process temperature or pressure indicator are read against the range plate. The controller is equipped with two internal pressure gauges to indicate the air supply pressure and the pneumatic output signal pressure.

Action

Pneumatic Controllers can be furnished in either direct or reverse action. A direct acting controller will increase the output signal as the input (temperature or pressure) of the application increases. A reverse acting controller will reduce the output signal as the input of the application increases. The action must be specified when ordering, but can be easily reversed in the field.

CHARACTERISTICS OF DIGITAL DATA

- **Digitized Value**
- Consider first analog-to-digital conversion (ADC) of analog data into a digital format. The format of the ADC output is an *n*-bit binary representation of the data.
- With *n*-bits it is possible to represent 2^n values, including zero. There is a finite *resolution* of the physical data being represented of one part in 2^n, and that means we now are ignorant about the value of the variable after it has been converted into the binary representation.
- **Sampled Data Systems:** For the control system to function correctly, certain conditions must be assumed about variations between samples. That is what sampled data systems are all about.

CHARACTERISTICS OF DIGITAL DATA

- **Sampling Rate** The key issue with respect to sampling in a computer-based controller is the rate at which samples must be taken.
- There is a maximum sampling rate in any system—that is, the time required to take a sample (ADC conversion time) plus the time required to solve the controller equations to determine the appropriate output (program execution time).
- There is a minimum sampling rate in any system that depends on the nature of the time variation of the sampled variable.

CHARACTERISTICS OF DIGITAL DATA

- **Linearization:**
- In many cases, the input binary number and the controlled variable are not linearly related. In such cases, it is necessary to execute a program that will linearize the binary number so that it is proportional to the controlled variable value.