NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

Signal Conditioning Elements of Mechatronics

Graduation Project

EE- 400

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ABSTRACT

The Mechatronics, process control, and their elements that perform all type of the systems, such as, measurement systems, display systems, and control systems. Also in the study of mechatronics there are four types of control systems: the principal control, the automatic control, the servomechatronic control, and the sequential control. Open-loop and close-loop, we use both these methods in the control systems to make the control easy. There are two general types in the processing control, the analog processing control and the digital processing control. Thus, we use Logic gates in the digital control.

The analog signal conditioning related to the standard techniques employed for providing signal compatibility and measurement in analog system, the need for analog signal conditioning was reviewed and resolved in to the requirement of signal level changes, linearization, signal conversion, and filtering and impedance matching. Bridge circuits are common example of a conversion process where a changing resistance is measured either by a current or a voltage signal. Operational amplifier (op-amps) is a special signal conditioning building block around which many special function circuit can be developed. The device was demonstrated in application involving amplifier, converter, integrators, and several other functions.

The digital signal conditioning depends on the digital electronic in the principle of working, digital electronic gates and comparators allow the implementation process Boolean equation. Digital to analog converter (DAC) are used to convert digital word in to analog number using a fractional number representation. An analog to digital converter (ADC) of the successive approximation type determines an output digital word for an input analog voltage in as many steps as bits to the word. Also in the word of digital signal conditioning elements there are many types, such as, multiplexing, modulation, and buffering.

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INTRODUCTION

The first engineering, that combine between two kinds of engineering, which spread in our world is called the Mechatronics engineering, this new technology is very Important for the electronic and mechanical control.

The component of an instrument that take the output signal from the sensor of a measurement system has generally to be processed in some way to make it suitable for the next stage of the operation is called the signal conditioning elements.

The first chapter is about the general information for the Mechatronics, in this chapter I concentrated to explain all the principles of mechatronics, and it will consider the overall process control loop, and it is description. Also in this chapter we shall be able to know, the definition of mechatronics, system, and measurement system. And to draw a block diagram of a process control loop with a description of each element.

The second chapter is about the analog signal conditioning elements, the purpose of this chapter is to familiarize the reader with the basic techniques of signal conditioning in process control. After you have read this chapter, you should be able to know the purpose and techniques of analog signal conditioning, design an application of the wheatstone bridge to convert resistance changes to voltage change, analyze the operation of types of filters to determine its effect on a signal, draw schematics of types of the basic op-amp signal conditioning circuit and provide their transfer function, design an analog signal conditioning system that converts a given input voltage variation into a required output voltage variation.

The third chapter is about digital signal conditioning elements. After this chapter we shall able to know convert a fractional binary number to decimal, octal, and hexadecimal representation, calculate the expected output voltage of a DAC for any digital input, explain the principle of a successive approximation ADC, draw a diagram of a general digital to analog converter and analog to digital converter, explain the principal operation of modulation.

1.THE MECHATRONICS

1.1 Introduction To Mechatronics

Mechanical engineering, as a widespread professional practice, experienced a surge of growth during the 19th century because it provided a necessary foundation for the rapid and successful development of the industrial revolution. At that time, mines needed large pumps never before seen to keep their shafts; transportation systems needed more than real power to move goods; structures began to stretch across ever wider abysses and to climb to dizzying heights; manufacturing moved from the shop bench to large factories; and to support these technical feats, people began to specialize build bodies of knowledge that formed the beginnings of the engineering disciplines.

Now, more than a century later, we are witnessing a new scientific and social in previous paragraph, this a new kind of science called by mechatronics. What is a mechatronics? and when did it start?

The word mechatronics was first coined by a senior engineer of a Japanese company; Yaskawa, in 1969, as combination of "mecha " of mechanisms and "tronics " of electronics and the company was granted the trademark rights on the world in 1971. The world soon received broad acceptance in industry and in order to allow its free use, Yaskawa elected to abandon its rights on the world in 1982. The world has taken a wider meaning since then and is now widely being used as a technical jargon to describe a philosophy in engineering technology, more than the technology itself. Mechatronics are the synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes.

A mechatronics system has two main components as shown in Figure 1.1. The controlled system is the mechanical process that is in contact with the world with all of its sensors and actuators. The distinguishing features of a mechatronic system from other systems are the three sub-systems of the controlling system used for perception, knowledge representation and planning and control. The intelligence is usually embedded in the planning and control sub-system. Here, based on the information gathered from the sensors, computational intelligence methodologies are exploited to plan a course of action that will enable the controlled system to achieve the given tasks.

Conventional microprocessors, artificial neural networks, fuzzy logic and probabilistic reasoning are among the tools used in the sub-system for information processing and decision-making.

In the design now of car, robots machine tools, washing machine, cameras, and many other machines, such as integrated approach to engineering design is increasingly being adopted. The integration across the traditional boundaries of mechanical engineering, electronics and control engineering has to occur at the earliest stage of the design process if cheaper, more reliable, more flexible systems are to be developed.

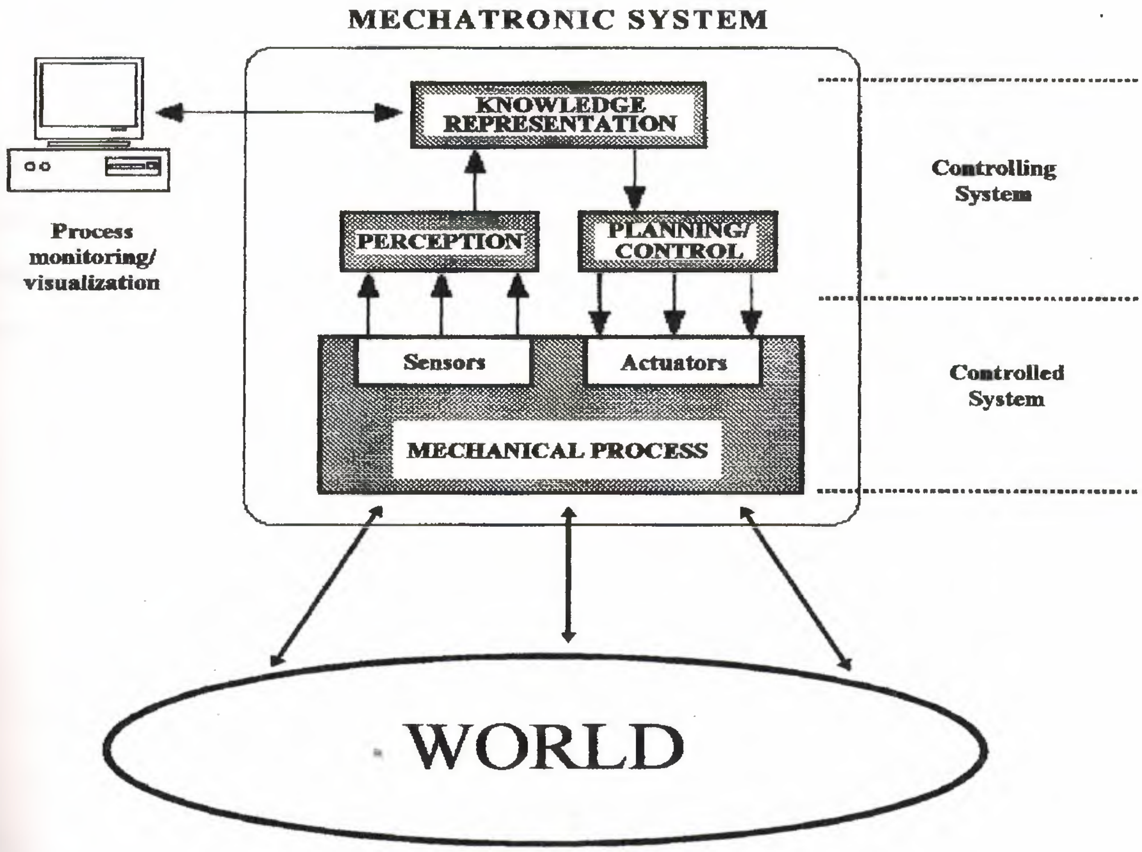


Figure 1.1 The architecture of a mechatronic system

1.2 Systems

Mechatronics involves, what are termed, systems. A system can be thought of as a black box, which has an input and an output. It is a black box because we are not concerned with what goes on inside the box but only the relationship between the output and the input.

Thus, for example, a motor may be thought of as a system, which has as its input electric power and as output the rotation of a shaft. Figure 1.2 shows a representation of such a system.

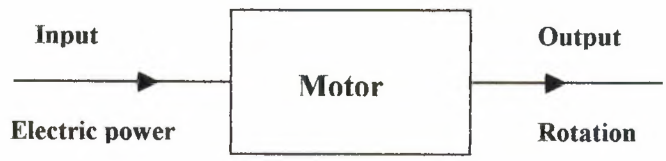


Figure 1.2 An example of a system

A measurement system can be thought of as a black box, which is used for making measurements. It has as its input the quantity being measured and its output the value of that quantity. For example, a temperature measurement system, i.e. a thermometer, has an input of temperature and an output of a number on a scale. Figure 1.3 shows a representation of such a system.

Figure 1.3 An example of a measurement system

A control system can be thought of as a black box, which is used to control its output to some particular value or particular sequence of values. For example, a central heating control system has, as its input the temperature required in the house and as its output the house at that temperature, i.e. you dial up the required temperature on the thermostat or controller and the heating furnace adjusts itself to produce that temperature. Figure 1.4 shows a representation of such a system.

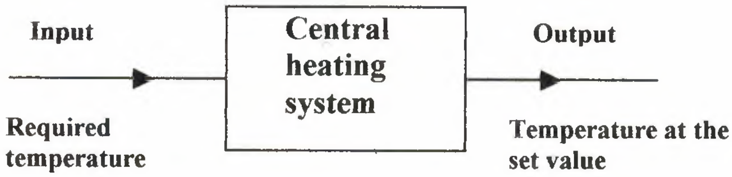


Figure 1.4 Measurement system

1.3 Measurement System

A fundamental part of many mechatronic systems is a measurement system that is composed of the three basic illustrated in figures 1.5.

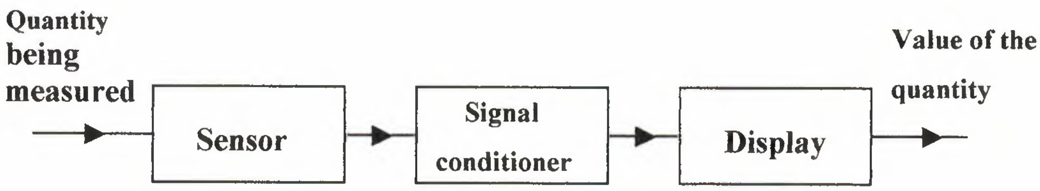


Figure 1.5 A measurement system and its constituent elements

1.3.1 The Sensors

A sensing device that convert a physical input in to an output, also we can say the sensor which responds to the quantity being measured by giving as its output a signal which is related to the quantity. For example, a thermocouple is a temperature sensor. The input to the sensor is a temperature and the output is an e.m.f. Which is related to the temperature value. A Bourdon pressure gauge has a curled tube, which straightens out to some extent when the pressure inside it is increased.

1.3.2 A signal conditional

Which takes the signal from the sensor and converts it into a condition as filtering, amplification, or other signal conditional, which is suitable for either display, or, in the case of a control system, for use to exercise control. Thus, for example, the output from a thermocouple is a rather small e.m.f. and might be fed through an amplifier to obtain a bigger signal. The amplifier is the signal conditioner. A Bourdon pressure gauge has the curled tube output magnified by gearing to give a larger output.

1.3.3 A display system

Where the output from the signal conditioner is displayed. This might, for example, be a pointer moving across a scale, a digital readout, a computer, a hardcopy device, or a simply a display that maintains the sensor data for online monitoring.

These three building blocks of measurement systems come in many types with wide variations in cost and performance. It is important for designers and users of measurement systems to develop confidence in their use, to know their important characteristics and limitations, and to be able to select the best elements for the measurement task at hand.

Shown below in figure 1.6 an example of a measurement system (digital thermometer). The thermocouple is a transducer that converts temperature to a small voltage; the amplifier increases the magnitude of the voltage; the A/D (analog to digital) converter is a device that converts the analog voltage to a digital signal; and the LEDs (light emitting diodes) display the value of the temperature.

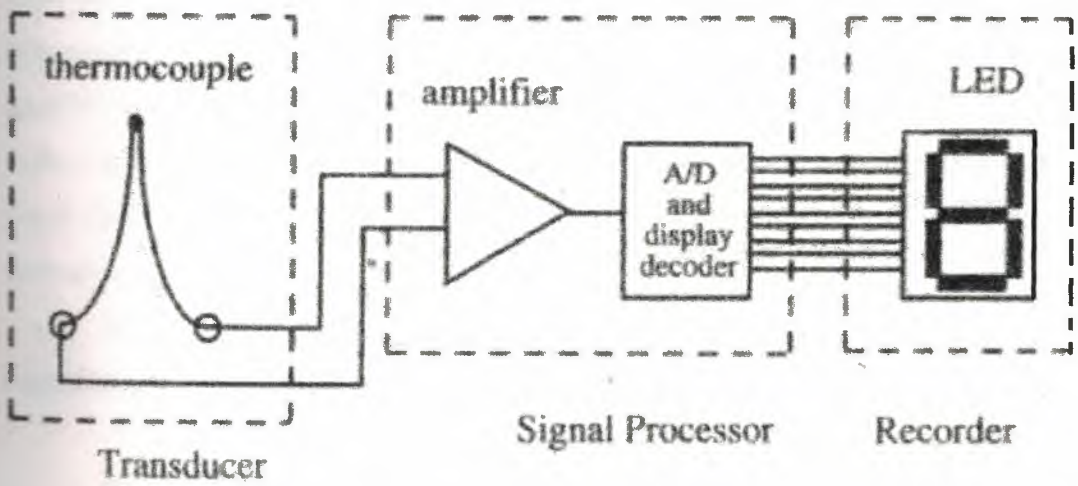


Figure 1.6 An example of a measurement system

1.4 control system

The basic strategy by which a control system operates is logical and natural. Infect, the same strategy is employed in living organisms. To maintain temperature, fluid flow rate, and a host of other biological functions. This is natural process control. The technology of artificial control was first developed using a human as an integral part of the control action.

When we learned how to use machines, electronics, and computers to replace the human function, the term automatic control came into use.

1.4.1 Process-Control Principles

In process control, the basic objective is to regulate the value of some quantity. To regulate means to maintain that quantity at some desired value regardless of external influences. The desired value is called the reference value or set point. The following paragraphs are uses the development of a control system for specific process control example to introduce some of the terms and expressions in the field.

The Process Figure 1.7 shows the process to be used for this discussion. Liquid is flowing into a tank at some rate Qin and out of the tank at some rate Qout. The liquid in the tank has some height or level h. It is known that the flow rate out varies as the square root of the height, so the higher the level the faster the liquid flows out. If the output flow rate is not exactly equal to the input flow rate, the tank will either empty, if Qout > Qin. Or overflow, if Qout < Qin .

This process has a property called self-regulation. This means that for some input flow rate. The liquid height will rise until it reaches a height for which the output flow rate matches the input flow rate. A self-regulating system does not provide regulation of a variable to any particular reference value. In this example the liquid level will adopt some value for which input and output flow rates are the same and there it will stay. But if the input flow rate changed, then the level would change also, so it is not regulated to a reference value.

Suppose we want to maintain the level at some particular value H in Figure 1.7, regardless of the input flow rate. Then something more than self-regulation is needed.

Human-Aided Control Figure 1.8 shows a modification of the tank system to allow artificial regulation of the level by a human. To regulate the level so that it maintains the value H it will be necessary to employ a sensor to measure the level. This has been provided via a "sight tube" S as shown in Figure 1.8. The actual liquid level or height is called the controlled variable. In addition, a valve has been added so the human can change the output flow rate. The output flow rate is called the manipulated variable or controlling variable.

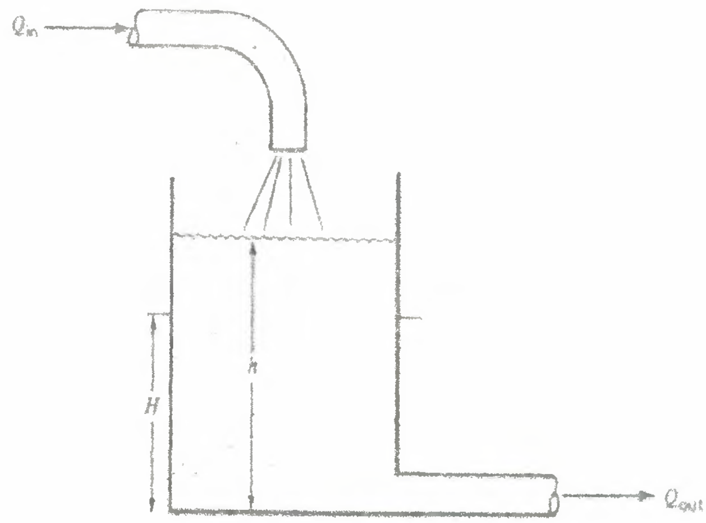


Figure 1.7 The objective is to regulate the level of liquid in the tank, h, to the value H.

Now the height can be regulated apart from the input flow rate using the following strategy: The human measures the height in the sight tube and compares the value to the set point. If the measured value is larger, the human opens the valve a little to let the flow out increase, and thus the level lowers toward the set point. If the measured value is smaller than the set point, the human closes the valve a little to decrease the flow out and allow the level to rise toward the set point.

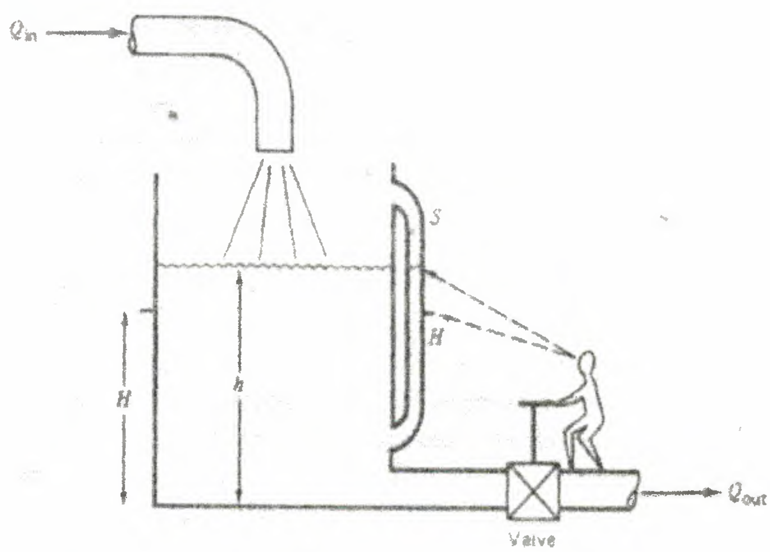


Figure 1.8 A human can regulate the level using a sight tube, S, to compare the level, h, to the objective, H. and adjust a valve to change the level.

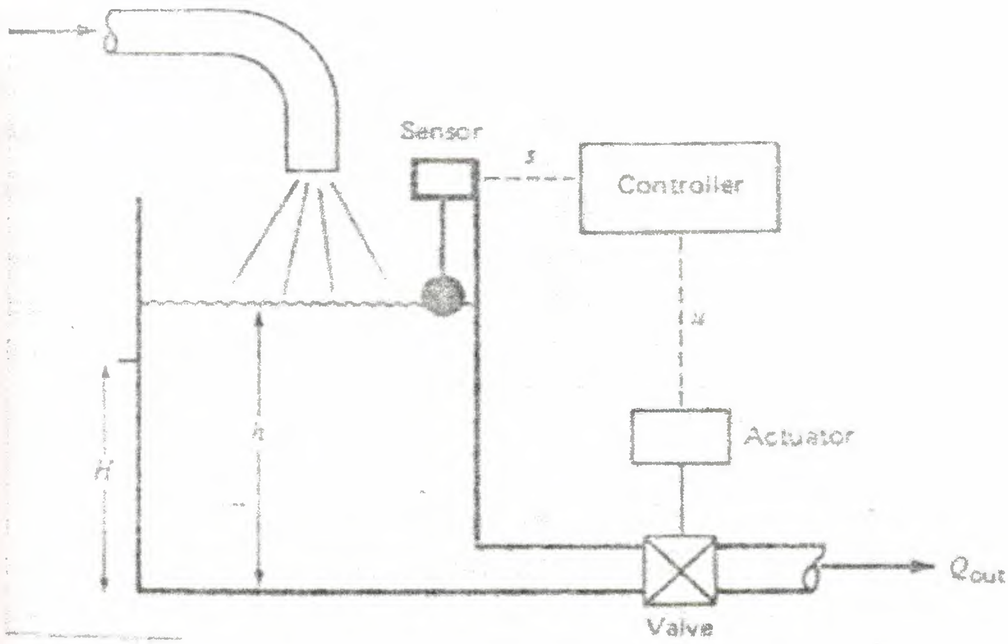


Figure 1.9 An automatic level-control system replaces the human by a controller and uses a sensor to measure the level.

By a succession of incremental opening and closing of the valve, the human can bring the level to the set point value H and maintain it there by continuous monitoring of the sight tube and adjustment of the valve. The height is regulated.

Automatic Control To provide automatic control, the system is modified as shown in Figure 1.9 so machines, electronics, or computers replace the operation of the human. An instrument called a sensor is added that is able to measure the value of the level and convert it into a proportional signals. This signal is provided as input to a machine, electronic circuit, or computer, called the controller. This performs the function of the human in evaluating the measurement and providing an output signal a to change the valve setting via an actuator connected to the valve by a mechanical linkage.

When automatic control is applied to systems like the one shown in Figure1.9, which are designed to regulate the value of some variable to a setpoint, it is called process control.

1.4.2 Servomechanisms

Another type of control system in common use, which has a slightly different objective from process control, is called servomechanism. In this case the objective is to force some parameter to vary in a specific manner. This may be called a tracking control system. Instead of regulating a variable value to a setpoint. The servomechanism forces the controlled variable value to follow variation of the reference value.

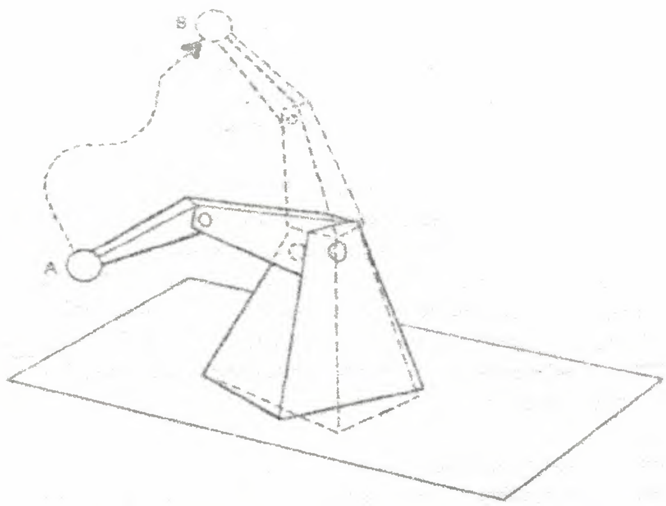


Figure 1.10 Servomechanism-type control systems are used to move a robot arm from point A to point B in a controlled fashion.

For example, in an industrial robot arm like the one shown in Figure 1.10, servonnechanisms force the robot arm to follow a path from point A to point B. This is done by controlling the speed of motors driving the arm and the angles of the arm parts.

The strategy for servomechanisms is similar to process-control systems, but the dynamic differences between regulation and tracking result in differences in design and operation of the control system. This text is directed toward process-control technology.

1.4.3 Open-Loop and Close-Loop Systems

There are two basic forms of control system, one being called open loop and the other closed loop. The difference between these can be illustrated by a simple example. Consider an electric fire which has a selection switch which allows a 1 kW or a 2 kW heating element to be selected. If a person used the fire to heat a room, he or she might just switch on the 1 kW element if the room is not required to be at too high a temperature. The room will heat up and reach a temperature which is only determined by the fact the 1 kW element was switched off and not the 2 kW element. If there is changes in the conditions, perhaps someone opening a window, there is no way the heat output is adjusted to compensate.

This is an example of open-loop control in that there is no information feed back to the element to adjust it and maintain constant temperature. The heating system with the electric fire could be made a closed loop system if the person has a thermometer and switches the 1 kW and 2kW elements on or off, according to the difference between the actual temperature and the required temperature, to maintain the temperature of the room constant. In this situation there is feedback, the input to the system being adjusted according to whether its output is the required temperature. This means that the input to the switch depends on the deviation of the actual temperature from the required temperature, the difference between them determined by a comparison element the person in this case. Figure 1.11 illustrates these two types of systems.

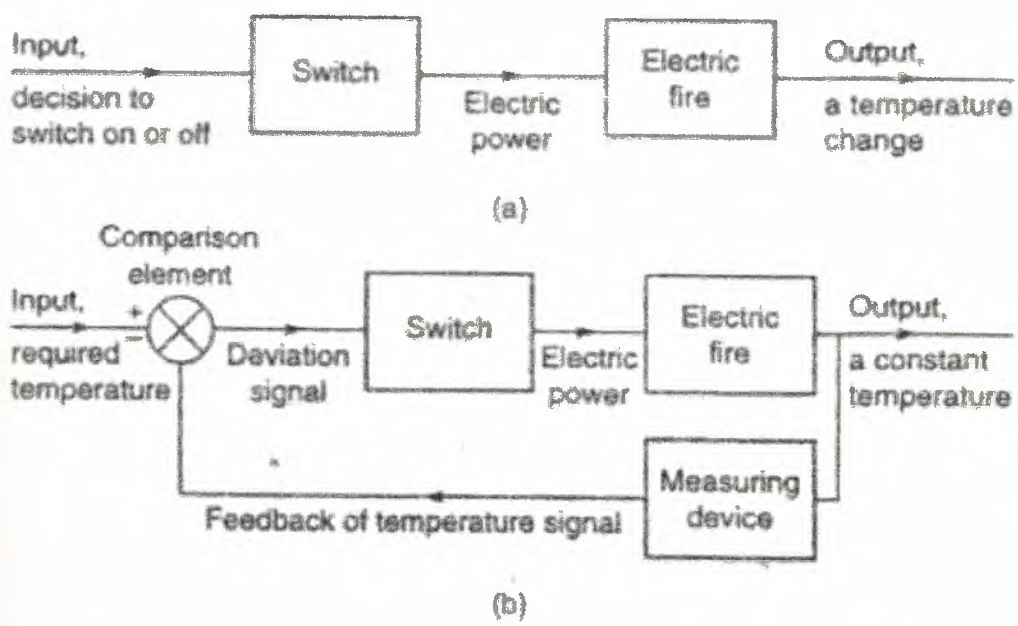


Figure 1.11 Heating a room: (a) an open-loop system, (b) a closed-loop system

To illustrate further the differences between open-loop and closed-loop systems, consider a motor. With an open-loop system the speed of rotation of the shaft might be determined solely by the initial setting of a knob, which affects the voltage applied to the motor. Any changes in the supply voltage, the characteristics of the motor as a result of temperature changes, or the shaft load will change the shaft speed but not be compensated for. There is no feedback loop. With a closed-loop system, however, the initial setting of the control knob will be for a particular shaft speed and this will be maintained by feedback, regardless of any changes in supply voltage, motor characteristics or load. In an open-loop control system the output from the system has no effect on the input signal. In a closed-loop control system the output does have an effect on the input signal, modifying it to maintain an output signal at the required value.

Open-loop systems have the advantage of being relatively simple and consequently low cost with generally good reliability. However, they are often inaccurate since there is no correction for error. Closed-loop systems have the advantage of being relatively accurate in matching the actual to the required values. They are, however, more complex and so more costly with a greater chance of breakdown as a consequence of the greater number of components.

1.4.4 Basic elements of a closed-loop system

Figure 1.12 shows the general form of a basic closed-loop system. It consists of the following elements:

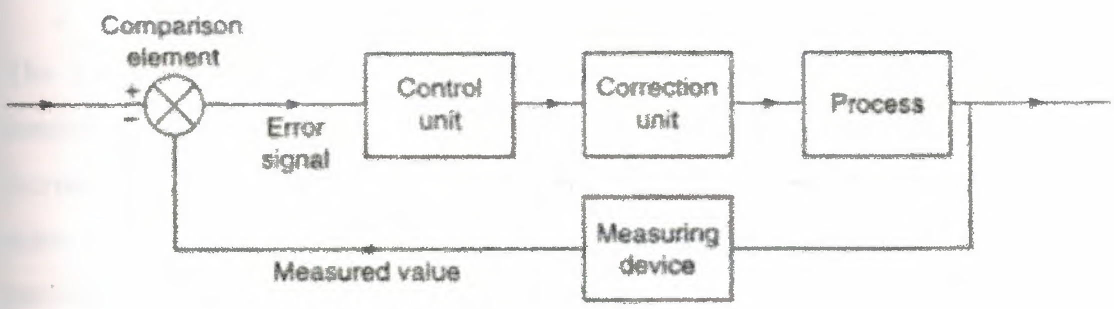


Figure 1.12 The elements of a closed-loop control system

- **Comparison element**

The comparison element compares the required or reference value of the variable condition being controlled with the measured value of what is being achieved and produces an error signal. It can be regarded as adding the reference signal, which is positive, to the measured value signal, which is negative in this case:

Error signal = reference value signal - measured value signal

The symbol used, in general, for an element at which signals are summed is a segmented circle, inputs going into segments. The inputs are all added, hence the feedback input is marked as negative and the reference signal positive so that the sum gives the difference between the signals, A feedback loop is a means where by a signal related to the actual condition being achieved is feed back to modify the input signal to a process. The feedback is said to be negative feedback when the signal, which is feedback subtracts from the input value. It is negative feedback that is required to control a system. Positive feedback occurs when the signal fed back adds to the input signal.

- **Control element**

The control element decides what action to take when it receives an error signal. It may be, for example, a signal to operate a switch or open a valve. The control plan being used by the element may be just to supply a signal, which switches on or off when there is an error, as in a room thermostat, or perhaps a signal, which proportionally opens or closes a valve according to the size of the error. Control plans may be Hard-wired systems in which the control plan is permanently fixed by the way the elements are connected together or programmable systems where the control plan is stored within a memory unit and may be altered by reprogramming it.

- **Correction element**

The correction element produces a change in the process to correct or change the controlled condition. Thus it might be a switch, which switches on a heater and so increases the temperature of the process or a valve, which opens and allows more liquid to enter the process. The term actuator is used for the element of a correction unit that provides the power to carry out the control action.

- **Process element**

The process is what is being controlled. It could be a room in a house with its temperature being controlled or a tank of water with its level being controlled.

- **Measurement element**

The measurement element produces a signal related to the variable condition of the process that is being controlled. It might be, for example, a switch, which is switched on when a particular position is reached or a thermocouple, which gives an e.m.f. related to the temperature.

With the closed loop system illustrated in figure 1.11 for a person controlling the temperature of a room, the various elements are:

- Controlled variable: the room temperature

- Reference value: the required room temperature
- Comparison element: the person comparing the measured value with the Required value of temperature
- Error signal: the difference between the measured and required Temperatures.
- Control unit: the person
- Correction unit: the switch on the fire.
- Process: the heating by the fire.

An automatic control system for the control of the room temperature could involve a temperature sensor, after suitable signal conditioning, feeding an electrical signal to the input of, computer where it is compared with the set value and an error signal generated. This is then acted on by the computer to give at its output a signal, which, after suitable signal conditioning, might be used to control a heater and hence the room temperature. Such a system can readily be programmed to give different temperature at different times of the day.

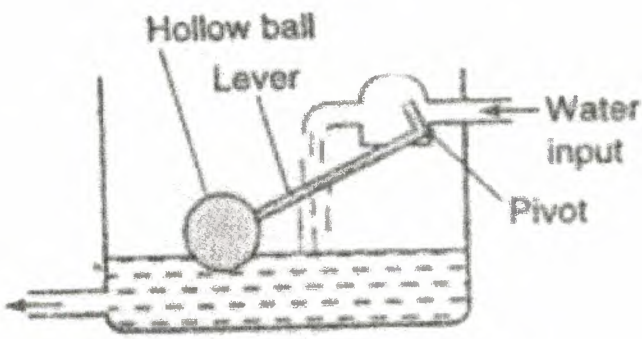


Figure 1.13 The automatic control of water level.

Figure 1.13 shows an example of a simple control system used to maintain a constant water level in a tank. The reference value is the initial setting of the lever arm arrangement so that it just cut off the water supply at the required level. When water is drawn from the tank the float moves downwards with the water level. This causes the lever arrangement to rotate and so allow water to enter the tank. This flow continues until the ball has risen to such; height that it has moved the lever arrangement to cut off the water supply. It is a closed-loop control system with the elements being:

- Controlled variable: water level in tank
- Reference value: initial setting of the float and level position
- Comparison element: the lever
- Error signal: the difference between the actual and initial settings of the Lever positions
- Control unit: the pivoted
- Correction unit: the flap opening or closing the water supply
- Process: the water level in the tank
- Measuring device: the floating ball and level

The above is an example of a closed-loop control system involving just mechanical elements. We could, however, have controlled the liquid level by means of an electronic control system. We thus might have had a level sensor supplying an electrical signal, which is used, after suitable signal conditioning, as an input to a computer where it is compared with a set value signal and the difference between them, the error signal, then used to give an appropriate response from the computer output. This is then, after suitable signal conditioning, used to control the movement of an actuator in a flow control valve and so determine the amount of water feed into the tank.

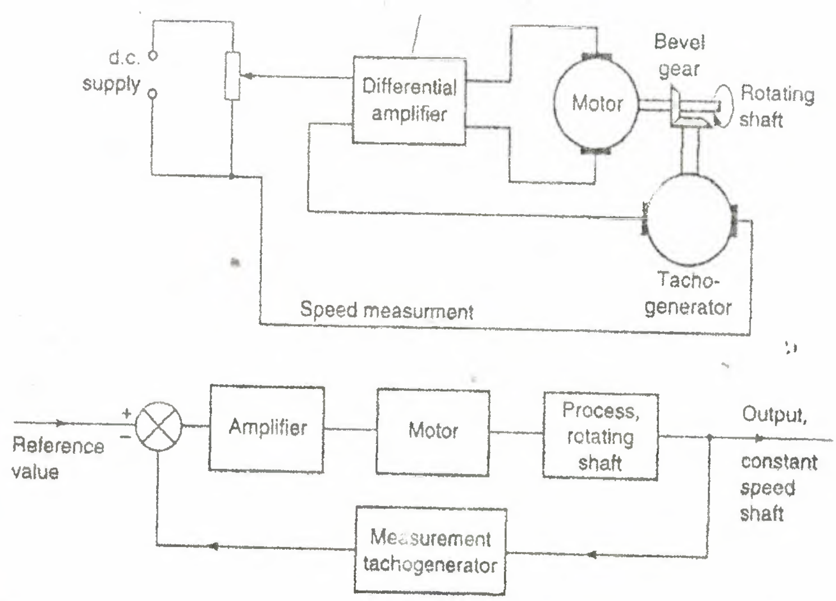


Figure 1.14 shaft speed control

Figure 1.14 shows a simple automatic control system for the speed of rotation of a shaft. A potentiometer is used to set the reference value, i.e. what voltage is supplied to the differential amplifier as the reference value for the required speed of rotation.

The differential amplifier is used to both compare and amplify the difference between the reference and feedback values, i.e. it amplifiers the error signal. The amplified error signal is then feed to a motor, which in turn adjusts the speed of the rotating shaft. The speed of the rotating shaft is measured using a tachogenerator, connected to the rotating shaft by means of a pair of bevel gears. The signal from the tachogenerator is then feed back to the differential amplifier.

1.4.5 Sequential Controllers

There are many situations where control is exercised by items being switched on or off at particular preset times or values to control processes and involve a step sequence of operations. After step I is complete then step 2 starts. When step 2 is complete then step 3 starts, etc. The term sequential control is used when control is such that actions are strictly ordered in a time sequence. This could be by sets of relays. Such mechanical switches are now more likely to have been replaced by microprocessors, such devices behaving like switches, which are user programmable.

As an illustration of sequential control, consider the domestic washing machine. The machine has to carry out a number of operations in the correct sequence. These may involve a program consisting of a pre-wash cycle when the clothes in the drum are given a wash in cold water, followed by a main wash cycle where they are washed in hot water, then a rinse cycle when the clothe; are rinsed with cold water a number of times, followed by spinning to remove water from the clothes. Each of these operations involves a number of steps, e.g. a pre-wash cycle involves opening a valve to fill the machine drum to the required level, closing the valve, switching on the drum motor to rotate the drum for a specific time, and operating the pump to empty the water from the drum. The system operating sequence is called a program and there will be a number of programs, which can be selected, the program depending on the type of clothes being washed in the machine. The sequence of instructions in each program is predefined and built into the controller used.

Figure 1.15 shows the basic washing machine system and gives a rough idea of its constituent elements. The system that has generally been used for the washing machine controller involves a set of cam-operated switches, i.e. mechanical switches.

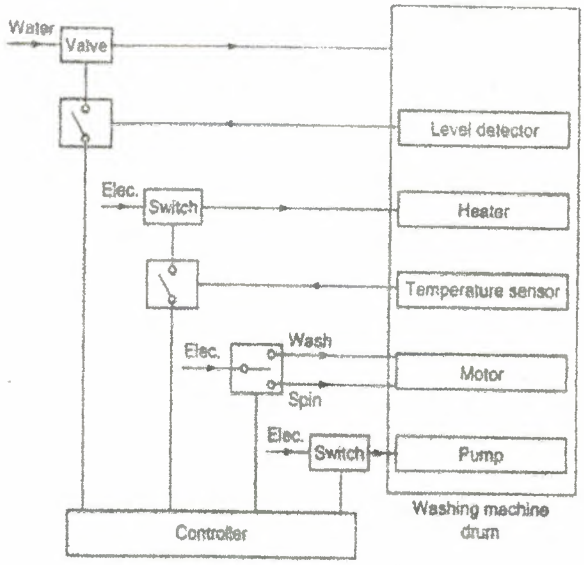


Figure 1.15 Washing machine system

Figure1.16 shows the basic principle of one such switch.

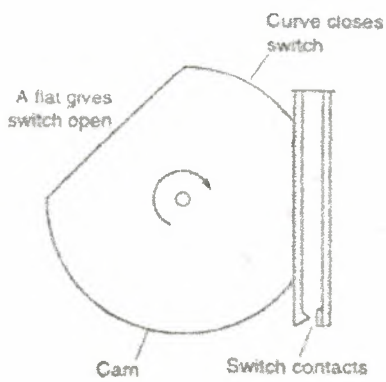


Figure 1.16 Cam-operated switch

When the machine is switched on, a small electric motor slowly turns the controller cams so that each in turn operates electrical switches and so switches on circuits in the correct sequence. The contour of a cam determines the time at which it operates a switch. Thus the Contours of the cams are the means by which the program is specified and stored in the machine. The sequence of instructions and the instructions used in a particular washing program are determined by the set of cams chosen.

For the pre-wash cycle an electrically operated valve is opened when a current is supplied and switched off when it ceases. This valve allows cold water into the drum for a period of time determined by the profile of the cam used to operate its switch.

However, since the requirement is a specific level of water in the washing machine drum, there needs to be another mechanism which will stop the water going into the tank, during the permitted time, when it reaches the required level. In series with the cam-operated switch is a water level switch. This is a sensor that gives a signal when the water level has reached the preset level and switches off the current to the valve.

For the main wash cycle, the cam has a profile such that it starts in operation when the pre-wash cycle is completed. It switches a current into a circuit lo open a valve to allow cold water into the drum. This is in series with a water level switch so that the water shuts off when the required level is reached. The cams then supply a current to activate a switch, which applies a larger current to an electric heater to heat the water. A temperature sensor is used to switch off the current when the water temperature reaches the preset value. The cams then switch on the drum motor to rotate the drum. This will continue for the time determined by the cam profile before switching off. Then a cam switches on the current to a discharge pump to empty the water from the drum.

The rinse part of the operation is now switched as a sequence of signals to open valves which allow cold water into the machine, switch it off, operate the motor to rotate the drum, operate a pump to empty the water from the drum, and repeat this sequence a number of times.

The final part of the operation is when a cam switches on just the motor, at a higher speed than for the rinsing, to spin the clothes.

1.4.6 Microprocessor-Based Controller

Microprocessors are now rapidly replacing the mechanical cam-operated controllers and being used in general to carry out control functions. They have the great advantage that a greater variety of programs become feasible. The term programmable logic controller is used for a microprocessor-based controller, which uses programmable memory to store instruct- ions and to implement functions such as logic, sequence, timing counting and arithmetic to control events.

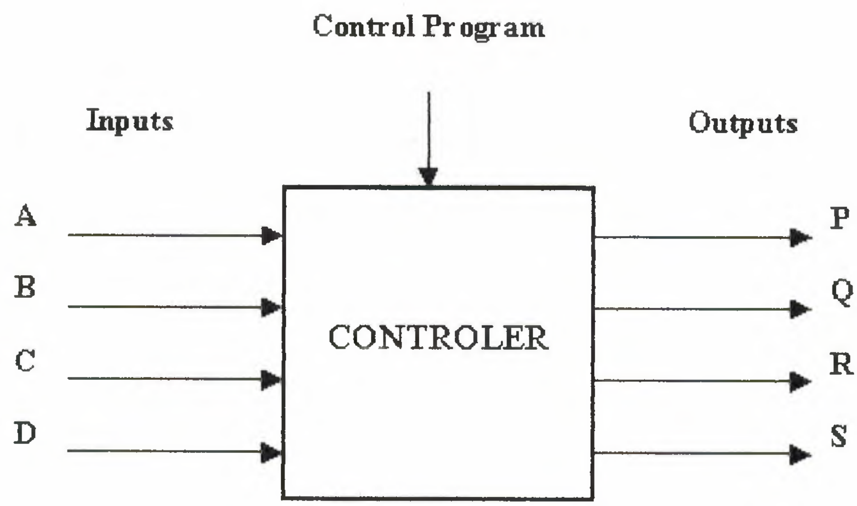


Figure 1.17 Programmable logic controller

Figure 1.17 shows the control action of a programmable logic controller, the inputs being signals from, say, switches being closed and the program used to determine how the controller should respond to the inputs and the output it should then give. Chapters 3 discuss microprocessors and their use as controllers (signal conditioning element).

1.5 Analog And Digital Processing Control

Until recently the functions of the controller in a control sophisticated electronic circuits performed system. Data were represented by the magnitude of voltages and currents in such systems. This is referred lo as analog processing.

Most modern control systems now employ digital computers to perform controller operations. In computers data are represented as binary numbers consisting of a specific number of bits. This is referred to as digital processing. The paragraphs that follow contrast the analog and digital approaches to control system operation.

1.5.1 Data Representation

The representation of data refers to how the magnitude of some physical variable is represented in the control loop. For example, if a sensor outputs a voltage whose magnitude varies with temperature, then the voltage represents the temperature Analog and digital system represent data in very different fashions.

Analog data an analog representation of data means that there is a smooth and continuous variation between a representation of a variable value and the value itself. Figure 1.18 shows an analog relationship between some variable c and its representation, b. Notice that for every value of c within the range covered there is a unique value of b. In principle, if c changes by some small amount Δc. Then b will change by a proportional amount. Δb.

The relationship in Figure 1.19 is called nonlinear because the same Δb does not result from fixed changes Δc over the range covered. This is described in more detail later in this chapter.

Digital Data The consequence of digital representations of data is that the smooth and continuous relation between the representation and the variable data value is lost. Instead, the digital representation can only take on discrete values. This can be seen in Figure 1.19 where a variable c is represented by a digital quantity N. Notice that arbitrarily small variations of c. such as $\Delta c1$. May not result in any change in N. The variable must change by more than some minimum amount. Depending on where in the curve, the change occurs, such as $\Delta c2$, before a change in representation is assured.

The reason for this discrete representation is that a finite number of binary number digits are used to represent data digitally. For example, suppose a variable voltage is to be represented digitally by a four-digit binary number. If each bit represents one volt, then the resulting representation is shown in Table 1.1. Note that the minimum resolution is one volt. The representation cannot distinguish between 4.25 and 4.75 volts because both are represented by the binary number 0100_2 .

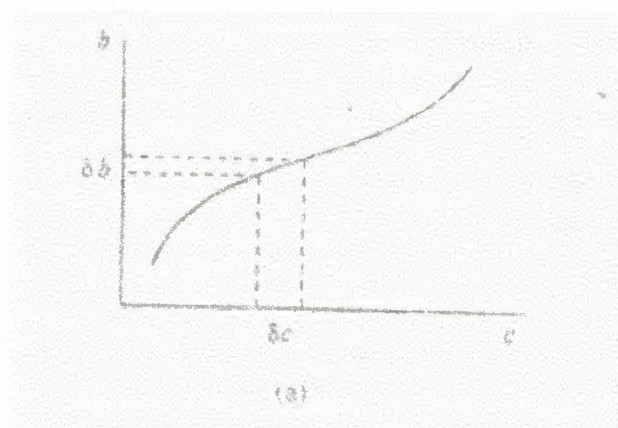


Figure 1.18 Analog Data

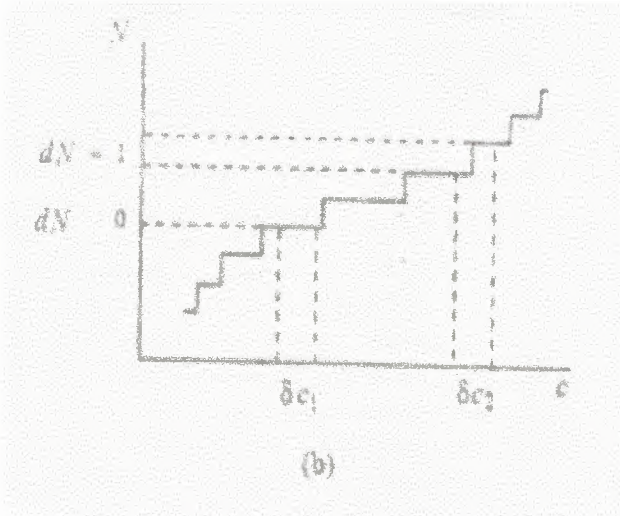


Figure 1.19 Digital Data

Data conversions special devices are employed to convert analog voltages into a digital representation. These are called analog-to-digital converters (ADCs).

In a control system the sensor often produces an analog output such as a voltage Then an ADC is used to convert that voltage into a digital representation for input to the computer. Figure 1.20 shows how some ADC might be used to convert voltage into a four-bit digital signal as illustrated in Table 1.1.

Digital-to-analog converters (DACs) convert a digital signal into an analog voltage. These devices are used to convert the control output of the computer into a form suitable for the final control elements.

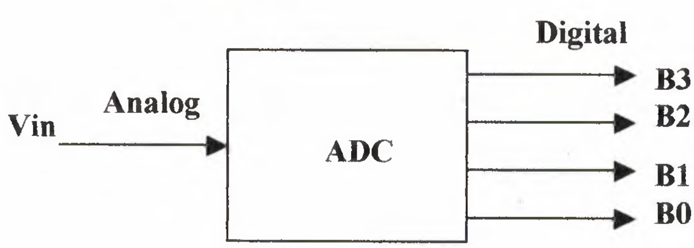


Figure 1.20 An ADC conveys analog data, such as voltage, into a digital representation, in this case four bits.

Table 1.1 Decimal-Binary Encoding

Voltage	Binary Word
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010

1.5.2 Analog Control

True analog control exists when all variables in the system are analog representations of another variable. Figure 1.21 shows a process in which a heater is used to control temperature in an oven. In this case. However, the heater output Q is an analog of the excitation voltage VQ, and thus heat can be varied continuously. Notice that every signal is an analog: V_T an analog of T, the error E an analog of the difference between the reference, Vref, and the temperature voltage, V_T. The reference is simply the voltage that would result from measurement of the specified reference temperature, T_{ref}.

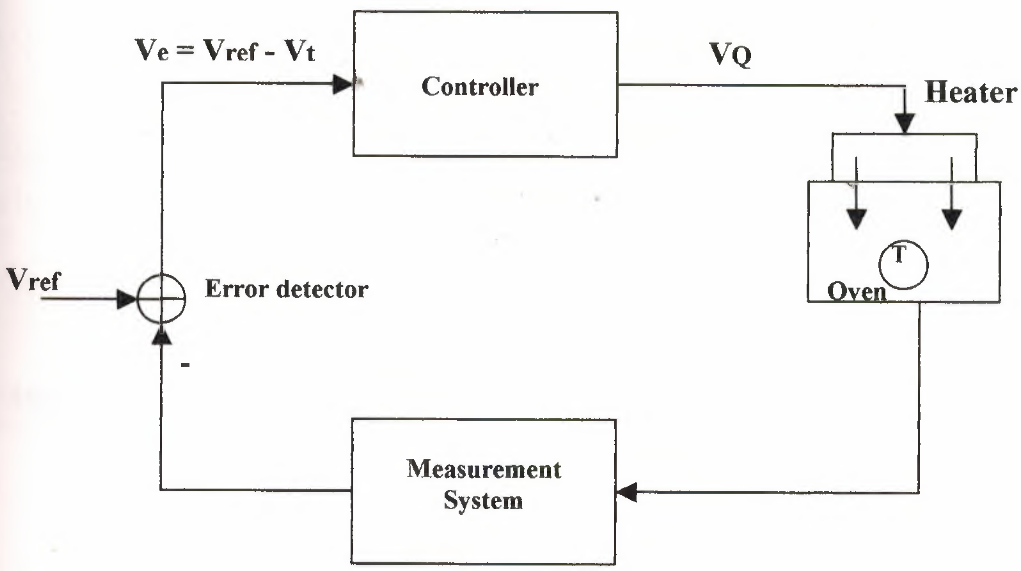


Figure 1.21 An analog control system such as this allows continuous variation of some parameter, such as heat input, as a function of error.

1.5.3 Digital Control

True digital control involves the use of a computer in modern applications, although in the past digital logic circuits were also used. There are two approaches to using computers for control. Supervisory Control When computers were first considered for applications in control systems, they did not have a good reliability: they suffered frequent failures and breakdown. The necessity for continuous operation of control system precluded the use of computers to perform the actual control operations. Supervisory control emerged as an intermediate step wherein the computer was used to monitor the operation of analog control loops and to determine appropriate set points. A single computer could monitor many control loops and use appropriate software to optimize the set points for the best overall plant operation. If the computer failed, the analog loops kept the process running using the last set points until the computer came back on line.

Figure 1.22 shows how a supervisory computer would be connected to the analog heater control system of figure 1.21 Notice how the ADC and DAC provide interface between the analog signals and the computer.

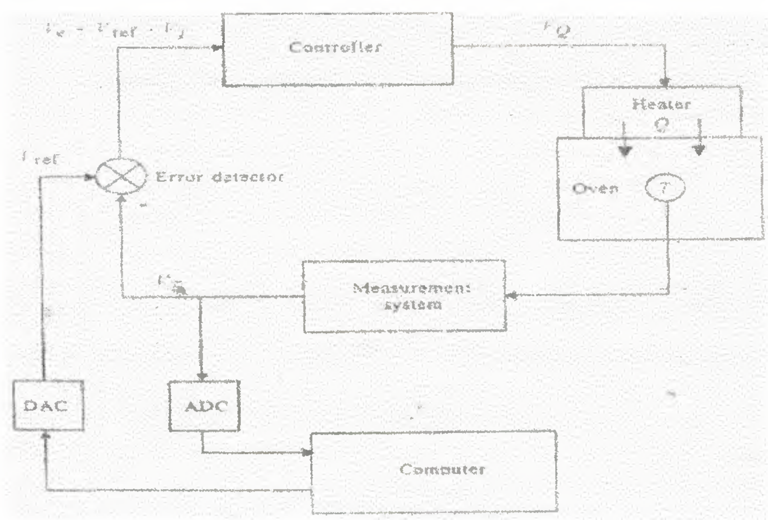


Figure 1.22 In supervisory control, the computer monitors measurements and updates set points, but the loops are still analog in nature.

Direct Digital Control (DDC). As computers have become more reliable and miniaturized, they have taken over the controller function. Thus, the analog-processing loop is discarded. Figure 1.23 shows how, in a full computer control system, the operations of the controller have been replaced by software in the computer. The ADC and DAC provide interface with the process measurement and control action. The computer inputs a digital representation of the temperature, N_T, as an analog-to-digital conversion of the voltage. V_T. Error detection and controller actions are determined by software. The computer then provides output directly to the heater via a digital representation, N_Q, which is converted to the excitation voltage V_Q by the DAC.

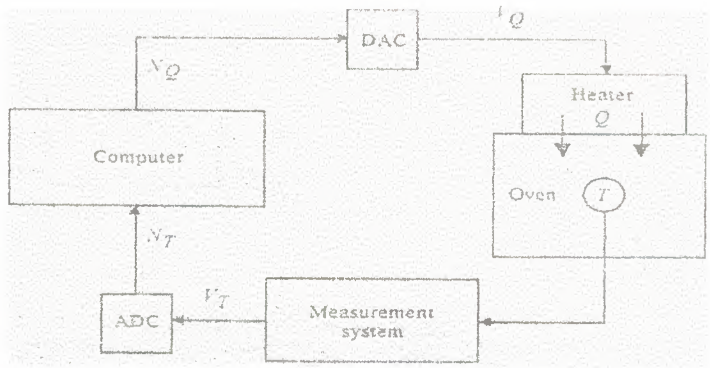


Figure 1.23 This direct digital control system lets the computer perform the error detection and controller functions.

1.6 Logic gates

The relationships between inputs to a logic gate and the outputs can be tabulated in a form known as a truth table. This specifies the relation- ships between the inputs and outputs.

1.6.1 AND gate

Thus for an AND gate with inputs A and B and a single output Q, we will have a 1 output when, and only when, A = 1 and B = 1. All other combinations of A and B will generate a 0 output. We can thus write the truth table as:

A	B	OUTPUT
0	0	0
0	1	0
1	0	0
1	1	1

The Boolean symbol for AND is a dot (.); this can be omitted, and usually is," A AND B" is written A. B, or simply AB.

1.6.2 OR gate

An OR gate with inputs A and B gives an output of a 1 when A or B is 1. We can visualize such a gate as an electrical circuit involving two switches in parallel. When switch or B is closed then there is a current. The following is the truth table:

A	B	OUTPUT
0	0	0
0	1	1
1	0	1
1	1	1

The Boolean symbol for OR is +. "A OR B" is written A + B.

1.6.3 NOT gate

A NOT gate has just one input and one output, giving a 1 output when the input is 0 and a 0 output when the input is 1. The NOT gate gives an output which is the inversion of the input and is called an inverter. The following is the truth table:

INPUT	OUTPUT
1	0
0	1

The Boolean symbol for NOT is a bar over the symbol, or sometimes a prime symbol. "NOT A" is written A, or A'. For the convenience of typesetters, the symbols /, * , -, and ' are often used, in place of the over bar , to indicate NOT; thus, "NOT A " might be written as any of the following: A`, -A, *A, /A, A/.

1.6.4 NAND gate

The NAND gate can be considered as a combination of an AND gate followed by a NOT gate. Thus when input A is 1 and input B is 1 there is an output of 0, all other inputs giving an output of 1. It is just the AND gate truth table with the outputs inverted. An alternative way of considering the gate is as an AND gate with a NOT gate applied to invert both the inputs before they reach the AND gate. The following is the truth table:

A	B	OUTPUT
0	0	1
0	1	1
1	0	1
1	1	0

1.6.5 NOR gate

The NOR gate can be considered as a combination of an OR gate followed by a NOT gate. Thus when input A or input B is I there is an output of 0. It is just the OR gate with the outputs inverted. An alternative way of considering the gate is as an OR gate with a NOT gate applied to invert both the inputs before they reach the OR gate. The following is the truth table:

A	B	OUTPUT
0	0	1
0	1	0
1	0	0
1	1	0

1.6.6 EXCLUSIVE gate

The EXCLUSIVE-OR gate (XOR) can be considered to be an OR gate with a NOT gates applied to one of the inputs to invert it before the inputs reach the OR gate. Alternatively it can be considered as an AND gate with a NOT gate applied to one of the inputs to invert it before the inputs reach the AND gate. The following is the truth table:

A	B	OUTPUT
0	0	1
0	1	0
1	0	0
1	1	1

The symbols used to represent the function of the gate are shown in the figure 1.24.

NOT GATE

AND GATE

OR GATE

NAND GATE

NOR GATE

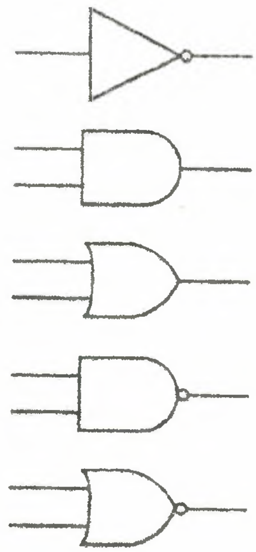


Fig.1.24 symbols of logic gates

1.7 The Mechatronics Approach

The domestic washing machine referred to earlier in this chapter used cam-operated switches in order to control the washing cycle. Such mechanical switches are being replaced by microprocessors. This can be considered an example of a mechatronics approach in that a mechanical system has become integrated with electronic controls. As a consequence, a bulky mechanical system is replaced by a much more compact microprocessor system, which is readily adjustable to give a greater variety of programs.

Mechatronics involves the bringing together of a number of technologies: mechanical engineering, electronic engineering, electrical engineering, computer technology, and control engineering. This can be considered to be the application of computer-based digital control techniques, through electronic and electric interfaces, to mechanical engineering problems. Mechatronics provides an opportunity to take a new look at problems, with mechanical engineers not just seeing a problem in terms of mechanical principles but also having to see it in terms of a range of technologies. The electronics, etc., should not be seen as a bolt-on item to existing mechanical hardware. There needs to be a complete rethink of the requirements in terms of what an item is required to do.

There are many applications of mechatronics in the mass-produced products used in the home. Microprocessor-based controllers are to be found in domestic washing machines, dish washers, microwave ovens, cameras, camcorders, watches, hi-fi, and video recorder systems, central heating thermostat controls, sewing machines, etc. They are to be found in cars in the active suspension, antiskid brakes, engine control, speedometer display, transmission, etc. A larger scale application of mechatronics is a flexible manufacturing engineering system (FMS) involving computer-controlled machines, robots, and automatic material conveying and overall supervisory control.

2. ANALOG SIGNAL CONDITIONING ELEMENTS

2.1 INTRODUCTION

Signal conditioning refers to operations performed on signals to convert them to a form suitable for interface with other elements in the process-control loop, in other ward, The output signal from the sensor of a measurement system has generally to be processed in some way to make it suitable for the next stage of the operation. The signal may be, for example, too small and have to be amplified, contain interference, which has to be removed, be non-linear and require linearisation, be analogue and have to be made digital, be digital and have to be made analogue, be a resistance change and have to be made into a current change, be a voltage change and have to be made into a suitable size current change, etc. All these changes can be referred to as signal conditioning. For example, the output from a thermocouple is a small voltage, a few millivolts. A signal-conditioning module might then be used to convert this into a suitable size current signal, provide noise rejection, linearisation. In this chapter, we are concerned only with analog conversions, where the conditioned output is still an analog representation of the variable. Even in applications involving digital processing. Some type or analog conditioning usually is required before analog-to-digital conversion is made. Specifics of digital signal conditioning are considered in Chapter 3.

2.1.1 Interfacing

Input and output devices are connected to a microprocessor system through ports. The term interface is used for the item that is used to make connections between devices and a port. Thus there could be inputs from sensors, switches, and keyboards and outputs to displays and actuators. The simplest interface could be just a piece of wire. However, the interface often contains signal conditioning and protection, the protection being to prevent damage to the microprocessor system. For example, inputs needed to be protected against excessive voltages or signals of the wrong polarity. Microprocessors require inputs which are digital, thus a conversion of analogue to digital signal is necessary if the output from a sensor is analogue. However, many sensors generate only a very small signal, perhaps a few millivolts. Such a signal is insufficient to be directly converted from analogue to digital without first being amplified. Signal conditioning might also be needed with digital signals to improve their quality. The interface may thus contain a number of elements. There is also the output from a microprocessor, perhaps to operate an actuator. A suitable interface is also required here. The actuator might require an analogue signal and so the digital output from the microprocessor needs converting to an analogue signal. There can also be a need for protection to stop any signal becoming inputted back through the output port to damage the microprocessor.

2.2 PRINCIPLES OF ANALOG SIGNAL CONDITIONING

A sensor measures a variable by converting information about that variable into a dependent signal of either electrical or pneumatic nature. To develop such transducers. We take advantage of fortuitous circumstances in nature where a dynamic variable influences some characteristic of a material. Consequently, there is little choice of the type or extent of such proportionality. For example, once we have researched nature and found that cadmium sulfide resistance varies inversely and nonlinearly with light intensity, we must then learn to employ this device for tight measurement within the confines of that dependence. Analog signal conditioning provides the operations necessary to transform a sensor output into a form necessary to interface with other elements of the process-control loop. We will confine our attention to electrical transformations.

We often describe the effect of the signal conditioning by the term transfer function. By this term we mean the effect of the signal conditioning on the input signal. Thus. A simple voltage amplifier has a transfer function of some constant that. When multiplied by the input voltage, gives the output voltage.

It is possible to categorize signal conditioning into several general types.

2.2.1 Signal-Level Changes

The simplest method of signal conditioning is to change the level of a signal. The most common example is the necessity to either amplify or attenuate a voltage level. Generally, process-control applications result in slowly varying signals where dc or low-frequency response amplifiers can be employed. An important factor in the selection of an amplifier is the input impedance that the amplifier offers to the sensor (or any other element that serves as an input). In process control, the signals are always representative of a process variable, and any loading effects obscure the correspondence between the measured signal and the variable value. In some cases, such as accelerometers and optical detectors, the frequency response of the amplifier is very important.

2.2.2 Linearization

As pointed out earlier, the process-control designer has little choice of the characteristics of a sensor output versus process variable. Often, the dependence that exists between input and output is nonlinear. Even those devices that are approximately linear may present problems when precise measurements of the variable are required.

Historically, specialized analog circuits were devised to linearize signals. For example, suppose a sensor output varied nonlinearly with a process variable, as shown in Figure 2.1. A linearization circuit, indicated symbolically in Figure 2.2. Would ideally be one that conditioned the sensor output so that a voltage was produced which was linear with the process variable, as shown in Figure 2.3. Such circuits are difficult to design and usually operate only within narrow limits.

The modem approach to this problem is to provide the nonlinear signal as input to a computer and perform the linearization using software. Virtually any nonlinearity can be handled in this manner and with the speed of modern computers in nearly real time.

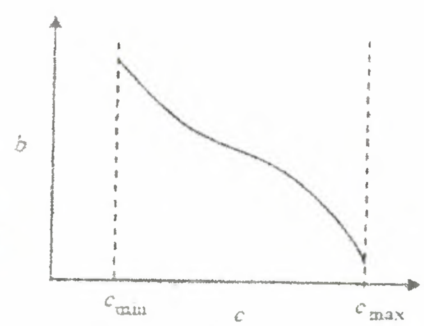


Figure 2.1 Output sensor varied nonlinearly

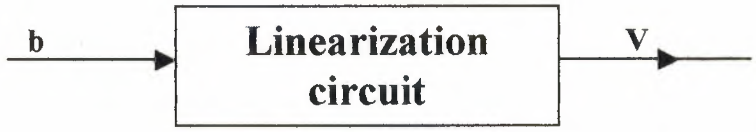


Figure 2.2 A linearization circuit

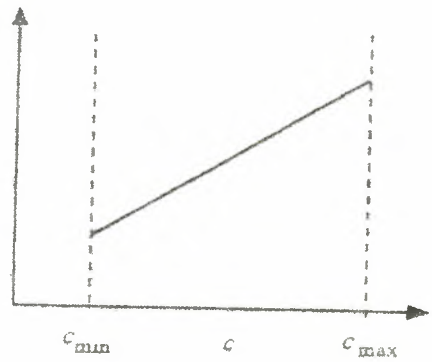


Figure 2.3 The ideal output of sensor

2.2.3 Conversions

Often, signal conditioning is used to convert one type of electrical variation into another. Thus, a large class of sensors exhibits changes of resistance with changes in a dynamic variable. In these cases, it is necessary to provide a circuit to convert this resistance change either to a voltage or a current signal. This is generally accomplished by bridges when the fractional resistance change is small and/or by amplifiers whose gain varies with resistance.

Signal Transmission, an important type of conversion is associated with the process-control standard of transmitting signals as 4-20 mA current levels in wire. This gives rise to the need for converting resistance and voltage levels to an appropriate current level at the transmitting end and for converting the current back to voltage at the receiving end. Of course, current transmission is used because such a signal is independent of load variations other than accidental shunt conditions that may draw off some current. Thus. Voltage-to-current and current-to-voltage converters are often required.

Digital Interface, the use of computers in process control requires conversion of analog data into a digital format by integrated circuit devices called analog-to-digital converters (ADCs). Analog signal conversion is usually required to adjust the analog measurement signal to match the input requirements of the ADC. For example, the ADC may need a voltage that varies between 0 and 5 volts, but the sensor provides a signal that varies from 30 to 80 mV. Signal conversion circuits can be developed to interface the output to the required ADC input.

2.2.4 Filtering and Impedance Matching

Two other common signal conditioning requirements are filtering and matching impedance.

Often, spurious signals of considerable strength are present in the industrial environment, such as the 60-Hz line frequency signals. Motor start transients also may cause pulses and other unwanted signals in the process-control loop. In many cases, it is necessary to use high-pass, low-pass, or notch filters to eliminate unwanted signals from the loop. Passive filters using only resistors, capacitors, and inductors can accomplish such filtering; or active filters, using gain and feedback.

Impedance matching is an important element of signal conditioning when transducer internal impedance or line impedance can cause errors in measurement of a dynamic variable. Both active and passive networks are employed to provide such matching.

2.2.5 Concept of Loading

One of the most important concerns in analog signal conditioning is the loading of one circuit by another. This introduces uncertainty in the amplitude of a voltage as it is passed through the measurement process. If this voltage represents some process variable, then we have uncertainty in the value of the variable.

Qualitatively, loading can be described as follows. Suppose the open circuit output of some element is a voltage, say V_x, when the element input is some variable of value x. Open circuit means that nothing is connected to the output. Loading occurs when we do connect something, a load, across the output, and the output voltage of the element drops to some value. $V_y < V_x$, different loads will result in different drops. Quantitatively, we can evaluate loading as follows. Thevenins theorem tells us that the output terminals of any element can be defined as a voltage source in series with output impedance. Let's assume this is a resistance (the output resistance) to make the description easier to follow. This is often called the Thevenin equivalent circuit model of the element.

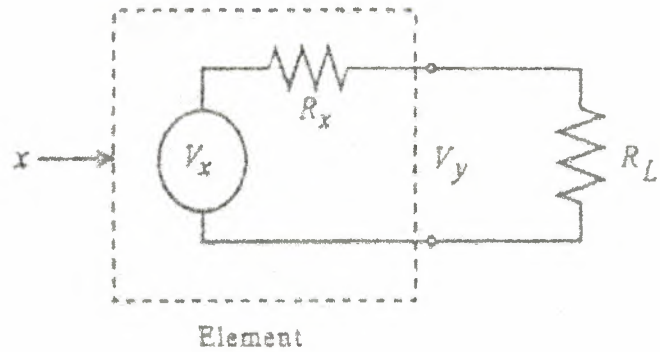


Figure 2.4 The Thevenin equivalent circuit of a sensor allows easy visualization of how loading occurs.

Figure 2.4 shows such an element modeled as a voltage Vx, and a resistance Rx. Now suppose a load, RL, is connected across the output of the element as shown in Figure 2.4. This could be the input resistance of an amplifier, for example. A current will flow and voltage will be dropped across Rx. It is easy to calculate that the loaded output voltage will thus be given by:

$$Vy = Vx * \{1-(Rx/(RL+Rx))\} \qquad (2.1)$$

The voltage that appears across the load is reduced by the voltage dropped across the internal resistance.

This equation shows how the effects of loading can be reduced, Clearly, the objective will be to make RL much larger than Rx, that is, RL >> Rx.

If the electrical quantity of interest is frequency or a digital signal, then loading is not important. That is, if there are enough signals left after loading to measure the frequency or to distinguish ones from zeros, there will be no error. Loading is important mostly when signal amplitudes are important.

2.3 PASSIVE CIRCUITS

Bridge and divider circuits are two passive techniques that have been extensively used for signal conditioning for many years. Although modern active circuits often replace these techniques, there are still many applications where their particular advantages make them useful.

Bridge circuits are primarily used as an accurate means of measuring changes in impedance. Such circuits are particularly useful when the fractional changes in impedance are very small.

Another common type of passive circuit involved in signal conditioning is for filtering unwanted frequencies from the measurement signal. It is quite common in the industrial environment to find signals that possess high- and/or low frequency noise as well as the desired measurement data. For example, a transducer may convert temperature information into a dc voltage, proportional to temperature. Because of the ever-present ac power lines, however, there may be a 60-Hz noise voltage impressed on the output that makes determination of the temperature difficult. A passive circuit consisting of a resistor and capacitor often can be used to eliminate both high- and low-frequency noise without changing the desired signal information.

2.3.1 Divider Circuits

The elementary voltage divider shown in Figure 2.5 often can be used to provide conversion of resistance variation into a voltage variation. The voltage of such a divider is given by the well-known relationship:

$$\mathbf{V_D = (R_2 . V_S) / (R_1 + R_2)} \qquad (2.2)$$

Where **V_S** : supply voltage

R_1, R_2 : divider resistors

Either R_1 or R_2 can be the sensor whose resistance varies with some measured variable.

It is important to consider the following issues when using a divider for conversion of resistance to voltage variation:

1. The variation of V_D with either R_1 or R_2 is nonlinear; that is, even if the resistance varies linearly with the measured variable, the divider voltage will not vary linearly.

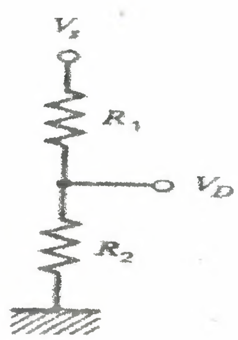


Figure 2.5 The simple voltage divider can often be used to convert resistance variation into voltage variation.

2. The effective output impedance of the divider is the parallel combination of R_1 and R_2. This may not necessarily be high, so loading effects must be considered.

3. In a divider circuit, current flows through both resistors: that is, power will be dissipated by both, including the sensor. The power rating of both the resistor and sensor must be considered.

2.3.2 Bridge Circuits

Bridge circuits are used to convert impedance variations into voltage variations. One of the advantages of the bridge for this task is that it can be designed so the voltage produced varies around zero. This means that amplification can be used to increase the voltage level for increased sensitivity to variation of impedance.

Another application of bridge circuits is in the precise static measurement of an impedance.

Wheatstone Bridge

The simplest and most common bridge circuit is the dc Wheatstone bridge, as shown in Figure 2.6. This network is used in signal conditioning applications where a sensor changes resistance with process variable changes. Many modifications of this basic bridge are employed for other specific applications. In Figure 2.6 the object labeled D is a voltage detector used to compare the potentials of points a and b of the network. In most modem applications the detector is a very high-input impedance differentia amplifier. In some cases, a highly sensitive galvanometer with relatively low impedance may be used. Especially for calibration purposes and spot measurement instruments.

For our initial analysis, assume the detector impedance is infinite, that is. An open circuit.

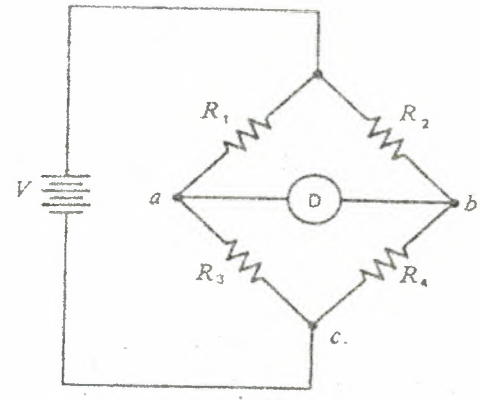


Figure 2.6 The basic dc Wheatstone bridge.

In this case the potential difference. ΔV between points a and b, is simply

$$\Delta V = Va - Vb \qquad (2.3)$$

where Va = potential of point a with respect to c

Vb = potential of point b with respect to c

The values of Va and Vb now can be found by noting that Va is just the supply voltage V divided between R_1 and R_3.

$$Va = (V^*R_3) / (R_1 + R_3) \qquad (2.4)$$

In a similar fashion, Vb is a divided voltage given by

$$Vb = (V^*R_4) / (R_2 + R_4) \qquad (2.5)$$

Where **V** = bridge supply voltage

If we now combine Equations (2.3), (2.4), and (2.5), the voltage difference or voltage Offset can be written.

$$\Delta V = \{(V^* R3) / (R1 + R3)\} - \{(V^* R4) / (R2 + R4)\} \qquad (2.6)$$

Using some algebra, the reader can show that this equation reduces to

$$\Delta V = \{V * [(R3^*R2 - R1^*R4) / (R1 + R3) * (R2 + R4)]\} \qquad (2.7)$$

Equation (2.7) shows how the difference in potential across the detector is a function of the supply voltage and the values of the resistors. Because a difference appears in the numerator of Equation (2.7), it is clear that a particular combination of resistors can be found that will result in zero difference and zero voltage across the detector, that is, a null. Obviously, this combination, from examination of equation (2.7), is:

$$\mathbf{R3*R2 = R1*R4} \qquad (2.8)$$

Equation (2.8) indicates that whenever a Wheatstone bridge is assembled and resistors are adjusted for a detector null. The resistor values must satisfy the indicated equality. It does not matter if the supply voltage drifts or changes; the null is maintained. Equations (2.7) and (2.8) underlie the application of Wheatstone bridges to process-control applications using high-input impedance detectors.

Galvanometer Detector, the use of a galvanometer as a null detector in the bridge circuit introduces some differences in our calculations because the detector resistance may be low and because we must determine the bridge offset as current offset. When the bridge is nulled. Equation (2.8) still defines the relationship between the resistors in the bridge arms. Equation (2.7) must be modified to allow determination of current drawn by the galvanometer when a null condition is not present. Perhaps the easiest way to determine this offset current is first to find the Thevenin equivalent circuit between points *a* and *b* of the bridge (as drawn in Figure 2.6 with the detector removed). The Thevenin voltage is simply the open circuit voltage difference between points *a* and *b* of the circuit. But wait! Equation (2.7) is the open circuit voltage, so

$$\mathbf{V_{Th} = \{ V * [(R3*R2 - R1*R4) / (R1 + R3) * (R2 + R4)] \}} \qquad (2.9)$$

The Thevenin resistance is found by replacing the supply voltage by its internal resistance and calculating the resistance between terminals *a* and *b* of the network. We may assume that the internal resistance of the supply is negligible compared to the bridge arm resistances. It is left as an exercise for the reader to show that the Thevenin resistance seen at points *a* and *b* of the bridge is

$$\mathbf{R_{Th} = \{(R1* R3)/(R1 + R3)\}+\{(R2* R4)/(R2 + R4)\}} \qquad (2.10)$$

The Thevenin equivalent circuit for the bridge enables us easily to determine the current through any galvanometer with internal resistance R_G. As shown in Figure 2.7. In particular, the offset current is:

$$\mathbf{I_G = \{V_{Th} / (R_{Th} + R_G)\}} \qquad (2.11)$$

Using this equation in conjunction with Equation (2.8) defines the Wheatstone bridge response whenever a galvanometer null detector is used.

Bridge Resolution, the resolution of the bridge circuit is a function of the resolution of the detector used to determine the bridge offset. Thus, referring primarily to the case where a voltage offset occurs, we define the resolution in resistance as that resistance change in one arm of the bridge that causes an offset voltage that is equal to the resolution of the detector. If a detector can measure a change of 100 μV. This sets a limit on the minimum measurable resistance change in a bridge using this detector. In general, once given the detector resolution, we may use Equation (2.7) to find the change in resistance that causes this offset.

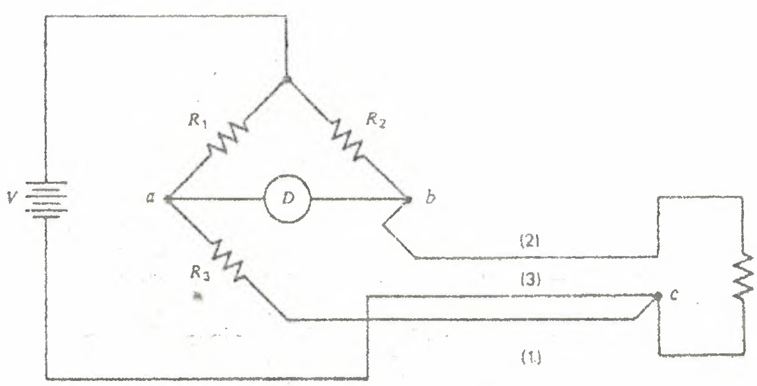


Figure 2.8 The remote sensor applications; a compensation system is used to avoid errors for lead resistance.

Lead Compensation, in many process-control applications, a bridge circuit may be located at considerable distance from the sensor whose resistance changes are to be measured. In such cases, the remaining fixed bridge resistors can be chosen to account for the resistance of leads required to connect the bridge to the sensor. Further more, any measurement of resistance can be adjusted for lead resistance to determine the actual resistance. Another problem exists that is not so easily handled. However. There are many effects that can change the resistance of the Ions lead wires on a transient basis, such as frequency, temperature, stress, and chemical vapors. Such changes will show up as a bridge offset and be interpreted as changes in the sensor output. This problem is reduced using lead compensation, where any changes in lead resistance are introduced equally in to two (both) arms of the bridge circuit, thus causing no effective change in bridge offset. Lead compensation is shown in Figure 2.8. Here we see that *R4,* which is assumed to be the sensor, has been removed to a remote location with lead wires (1), (2), and (3). Wire (3) is the power lead and has no influence on the bridge balance condition. If wire (2) changes in resistance because of spurious influences, it introduces this change into the *R4* leg of the bridge. Wire (1) is exposed to the same environment and changes by the same amount, but is in the *R3* leg of the bridge. Effectively, both *R3* and *R4* are identically changed, and thus Equation (2.8) shows that no change in the bridge null occurs. This type of compensation is often employed where bridge circuits must be used with long leads to the active element of the bridge.

Current Balance Bridge, one disadvantage of the simple Wheatstone bridge is the need to obtain a null by variation of resistors in bridge arms. In the past.

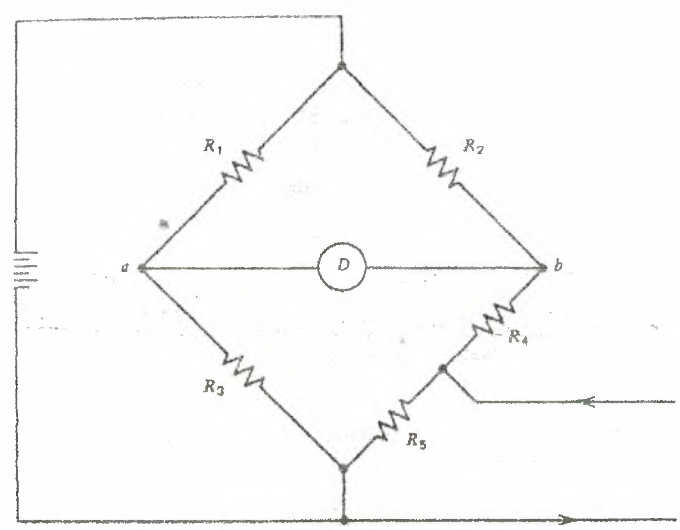


Figure 2.9 The current balance bridge.

Many process-control applications used a feedback system in which the bridge-offset voltage was amplified and used to drive a motor whose shaft altered a variable resistor to renull the bridge. Such a system does not suit the modern technology of electronic processing because it is not very fast. Is subject to wear, and generates electronic noise. A technique that provides for an electronic nulling of the bridge and that uses only fixed resistors (except as may be required for calibration) can be used with the bridge. This method uses a current to null the bridge. A closed-loop system can even be constructed that provides the bridge with a self-nulling ability.

The basic principle of the current balance bridge is shown in Figure 2.9. The standard Wheatstone bridge is modified by splitting one arm resistor into two, R4 and R5. A current 1 is fed into the bridge through the junction of R4 and R5 as shown. We now stipulate that the size of the bridge resistors is such that the current flows predominantly through R5. This can be provided for by any of several requirements. The least restrictive is to require

$$\mathbf{R4 \gg R5} \qquad (2.12)$$

Often, if a high-impedance null detector is used, the restriction of Equation (2.12) becomes

$$\mathbf{(R2 - R4) \gg R5} \qquad (2.13)$$

Assuming that either conditions of Equations (2.12) or (2.13) are satisfied, the voltage at point b is the sum of the divided supply voltage plus the voltage dropped across R5 from the current I.

$$\mathbf{Vb = \{V * (R4 + R5) / R2 + R4 + R5\} + I * R5} \qquad (2.14)$$

The voltage of point a is still given by Equation (2.4). Thus, the bridge offset voltage is given by $\Delta V = Va - Vb$, or

$$\mathbf{\Delta V = (V * R3 / R1 + R3)-(V * (R4+R5) / R2+R4+R5)-(I * R5)} \qquad (2.15)$$

This equation shows that a null is reached by adjusting the magnitude and polarity of the current I until *I*R5* equals the voltage difference of the first two terms. If one of the bridge resistors changes, the bridge can be renulled by changing current I. In this manner, the bridge is electronically nulled from any convenient current source. In most applications the bridge is nulled at some nominal set of resistances with zero current. Changes of a bridge resistor are detected as a bridge-offset signal that is used to provide the renulling current.

Temperature compensation, in many measurements involving a resistive sensor the actual sensing element may have to be at the end of long leads. Not only the sensor but also the resistance of these leads will be affected by changes in temperature. For example, a platinum resistance temperature sensor consists of a platinum coil at the ends of leads. When the temperature changes, not only will the resistance of the coil change but so also will the resistance of the leads. What is required is just the resistance of the coil and so some means has to be employed to compensate for the resistance of the leads to the coil. One method of doing this is to use three leads to the coil, as shown in figure 2.11. The coil is connected into the Wheatstone bridge in such a way that lead 1 is in series with the R3 resistor while lead 3 is in series with the platinum resistance coil R1. Lead 2 is the connection to the power supply. Any change in lead resistance is likely to affect all three leads equally, since they are of the same material, diameter and length and held close together. The result is that changes in lead resistance occur equally in two arms of the bridge and cancels out if R1 and R3 are the same resistance.

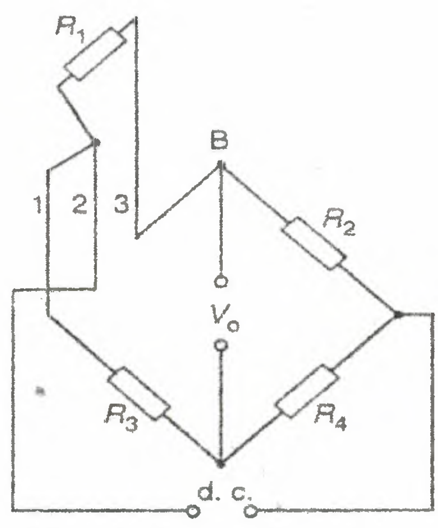


Figure 2.10 compensation for leads

The electrical resistance strain gauge is another sensor where compensation has to be made for temperature effects. The strain gauge changes resistance when the strain applied to it changes. Unfortunately, it also changes if the temperature changes. One way of eliminating the temperature effect is to use a dummy strain gauge. This is a strain gauge, which is identical to the one under strain, the active gauge, and is mounted on the same material but is not subject to the strain. It is positioned close to the active gauge so that it suffers the same temperature changes. Thus a temperature change will cause both gauges to change resistance by the same amount. The active gauge is mounted in one arm of a Wheatstone bridge (figure 2.11) and the dummy gauge in another arm so that the effects of temperature-induced resistance changes cancel out.

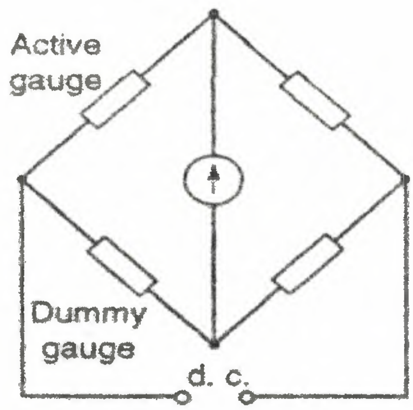


Figure 2.11 compensation with strain gauges

Strain gauges are often used with other sensors such as load cells or diaphragm pressure gauges. In such situations, temperature compensation is still required. While dummy gauges could be used, a better solution is to use four strain gauges. Two of them are attached so that when forces are applied they are in tension and the other two in compression. The load cell in figure 2.12 shows such a mounting. The gauges that are in Tension will increase in resistance while those in compression will decrease in resistance. As the gauges are connected as the four arms of a Wheatstone bridge (figure 2.12), then since all will be equally affected by any temperature changes the arrangement is temperature compensated. The arrangement also gives a much greater output voltage than would occur with just a single active gauge.

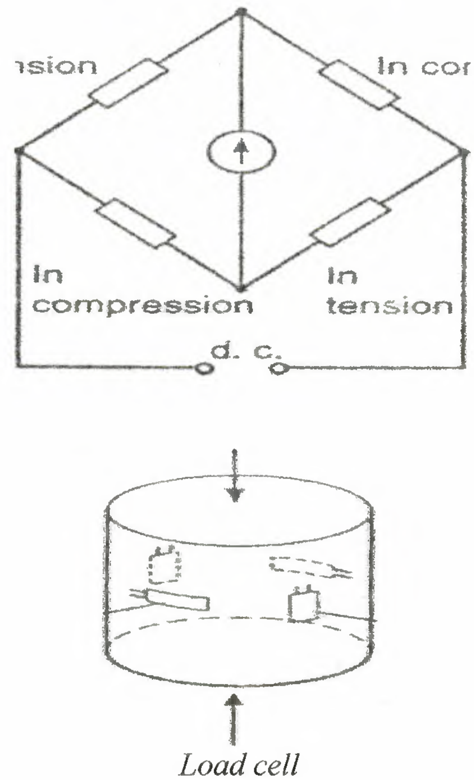


Figure 2.12 Four active arm strain gauge bridge

Ac Bridges, the bridge concept described in this can be applied to the matching of impedance in general, as well as to resistance. In this case, the bridge is represented as in figure 2.13 and employs an ac excitation, usually a sine wave voltage signal. The analysis of bridge behavior is basically the same as in the previous treatment, but impedances replace resistances. The bridge offset voltage then is represented as

$$\mathbf{\Delta E = E\ [(Z3Z2-Z1Z4)\ /\ (Z1+Z3)(Z2+Z4)]} \qquad (2.16)$$

ΔE = ac off set voltage

Where E = sine wave excitation voltage
Z1, Z2, Z3, Z4 = bridge impedances

A null condition is defined as before by a zero offset voltage ΔE = 0. From Equation (2.16), this condition is met if the impedances satisfy the relation:

$$\mathbf{Z2Z3 = Z1Z4} \qquad (2.17)$$

This condition is analogous to Equation (2.8) for resistive bridges.

A special note is necessary concerning the achievement of a null in ac bridges. In some cases, the null detection system is phase sensitive with respect to the bridge excitation signal. In these instances, it is necessary to provide a null of both the in-phase and quadrature (90° out-of-phase) signals before Equation (2.17) applies.

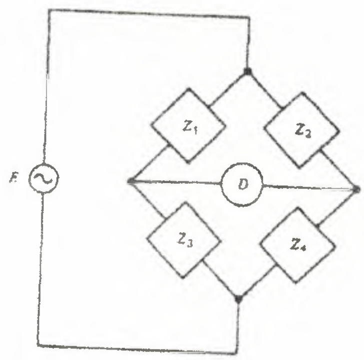
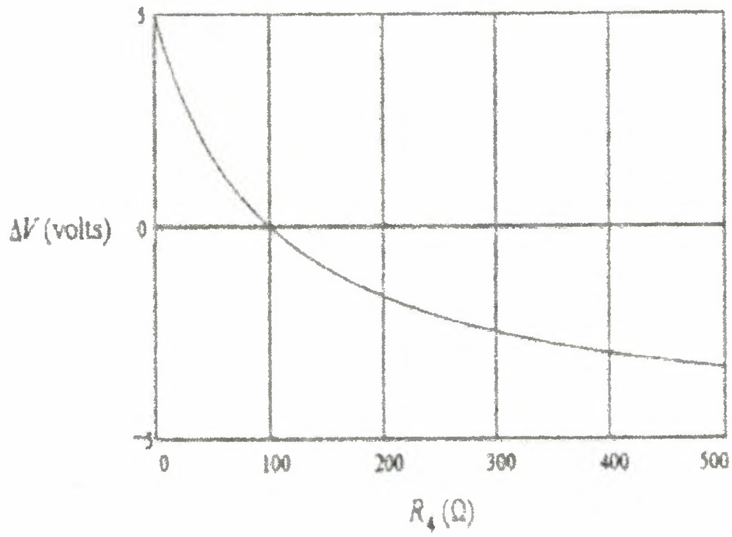


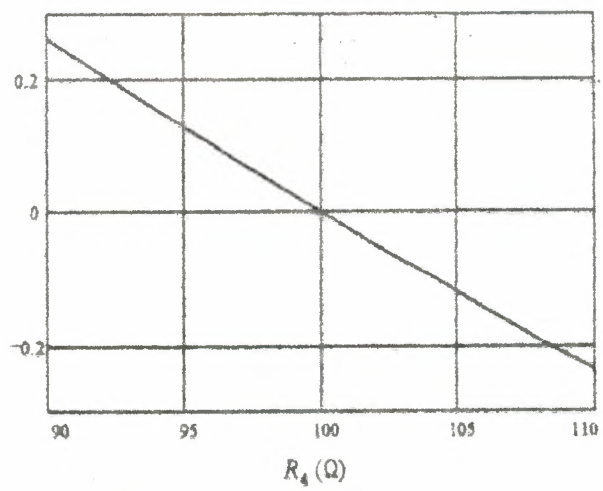
Figure 2.13 A general bridge circuit

Bridge Applications, The primary application of bridge circuits in modern process-control signal conditioning is to convert variations of resistance into variations of voltage. This voltage variation is then further conditioned for interface to an ADC or other system. It is thus important to note that the variation of bridge offset as given by Equation (2.7) is nonlinear with respect to any of the resistors. The same nonlinearity is present in ac bridge offset as given by Equation (2.16) Thus. If a sensor has impedance that is linear with respect to the variable being measured, such linearity is lost when a bridge is used to convert this to a voltage variation. Figure 2.14a shows how ΔV varies with R4 for a bridge with R1 = R2 = R3 = 100Ω. Note the nonlinearity of ΔV with *R4* as it varies from 0 to 500 Ω.

If the range of resistance variation is small and centered about the null value then the nonlinearity of voltage versus resistance is small. Figure 2.14b shows that if the range of variation of *R4* is small (90 to 110 Ω), then the variation of ΔV with *R4, on* an expanded scale, is relatively linear. Amplifiers can be used to amplify this voltage variation, since it is centered about zero, to a useful range.



(a)



(b)

Figure 2.14 Bridge off-null voltage is clearly nonlinear for large-scale changes inresistance, but for small ranges of resistance change the off-null voltage is nearly linear.

2.3.3 Filtering

The term filtering is used to describe the process of removing a certain band of frequencies from a signal and permitting others to be transmitted. The range of frequencies passed by a filter is known as the pass band, the range not passed as the stop band and the boundary between stopping and passing as the cut-off frequency. Filters are classified according to the frequency ranges they transmit or reject. A low-pass filter (figure 2.15(a)) has a pass band, which allows all frequencies from 0 up to some frequency to be transmitted. A high-pass filter (figure 2.15(c)) has a pass band, which allows all frequencies from some value up to infinity to be transmitted. A band-pass filter (figure 2.15(c)) allows all the frequencies within a specified band to be transmitted. A band-stop filter (figure 2.15(d)) stops all frequencies with a particular band from being transmitted.

The term passive is used to describe a filter made up using only resistors, capacitors and inductors, the term active being used when the filter also involves an operational amplifier. Passive filters have the disadvantage that the current that is drawn by the item that follows can change the frequency characteristic of the filter. This problem does not occur with an active filter.

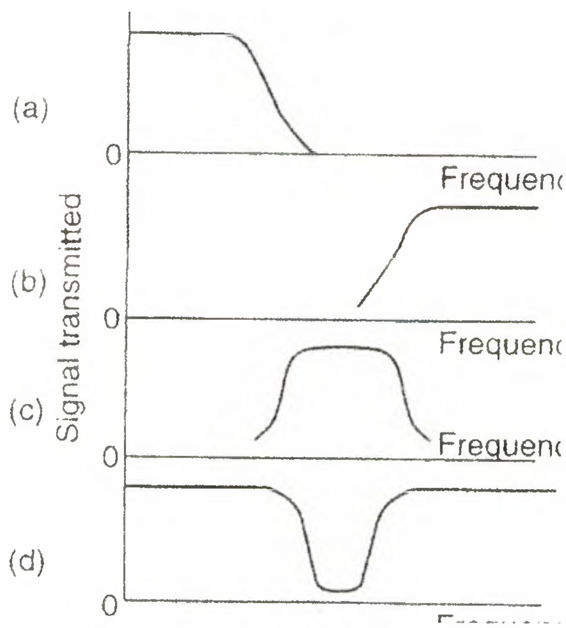


Figure 2.15 Filters: (a) low pass, (b) high pass, (c) band pass, *(d)* band stop

Low-pass RC Filter The simple circuit shown in Figure 2.16 is called a low-pass RC filter. It is called low-pass because it blocks high frequencies and passes low frequencies. It would be most desirable if a low-pass filter had a characteristic such that all signals with frequency above some critical value are simply rejected. Practical filter circuits approach that ideal with varying degrees of success.

In the case of the RC low-pass filter, the variation of rejection with frequency is shown in Figure 2.17. In this graph the vertical is the ratio of output voltage to input voltage without regard to phase. When this ratio is one, the signal is passed without effect:

when it is very small or zero. the signal is effectively blocked.

The horizontal is actually the logarithm of the ratio of the input voltage signal frequency to a critical frequency. This critical frequency is that frequency for which the ratio of the output to the input voltage is 0.707, In terms of the resistor and capacitor, the critical frequency is given by

$$\mathbf{Fc = 1 / (2\pi RC)} \qquad (2.18)$$

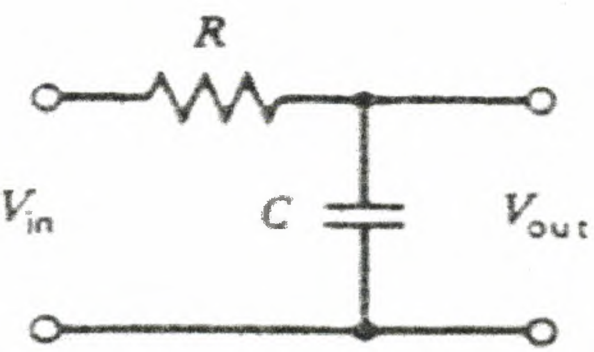


Figure 2.16 Circuit for the low-pass RC filter

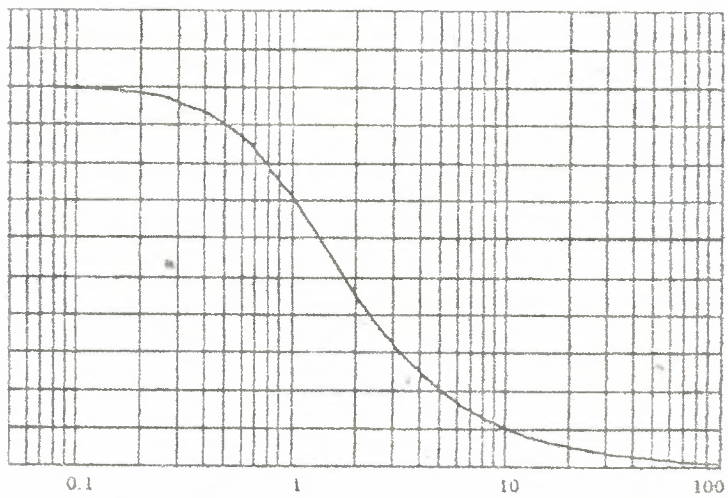


Figure 2.17 response of the low-pass RC filter as a function of frequency ratio

The voltage ratio for any signal frequency can be determined graphically from Figure 2.17 or can be computed by:

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{[1 + (f/f_c)^2]^{1/2}}$$

(2.19)

High-Pass RC Filter, A high-pass filter passes high frequencies (no rejection) and blocks (rejects) low frequencies. A filter of this type can be constructed using a resistor and capacitor, as shown in the schematic of Figure 2.18. Similar to the low-pass filter, the rejection is not sharp in frequency but distributed over a range around a critical frequency. This critical frequency is defined by the same value-as last equation-as for the low-pass filter.

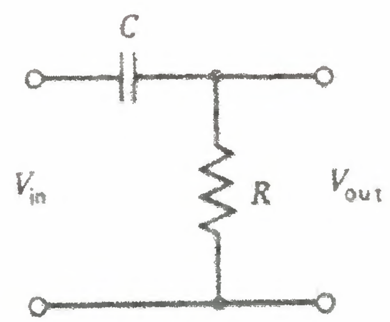


Figure 2.18 Circuit for the high-pass RC filter

The graph of voltage output to input versus logarithm of frequency to critical frequency is shown in Figure 2.19. Note that the magnitude of Vout/Vin = 0.707 when the frequency is equal to the critical frequency.

An equation for the ratio of output voltage to input voltage as a function of the frequency for the high-pass filter is found to be:

$$|V_{out}/V_{in}| = \frac{(f/f_c)}{[1 + (f/f_c)^2]^{1/2}}$$

(2.20)

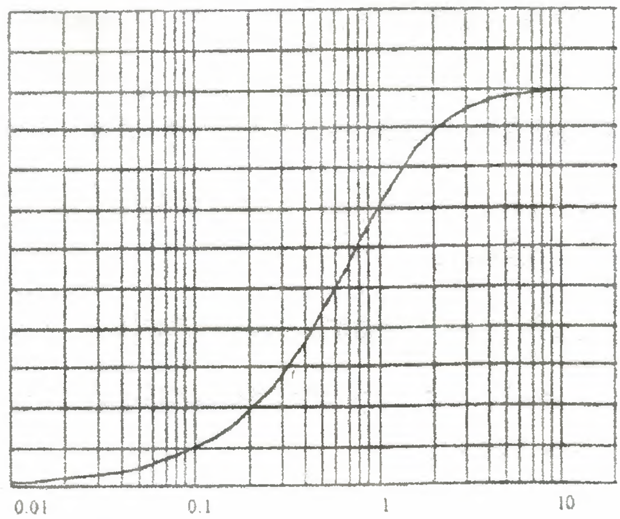


Figure 2.19 Response of the high-pass RC filter as a function of frequency ratio.

Practical Considerations

There are a number of issues that arise when designing a system, which will use the *RC* high-pass or low-pass filters. Consider the following items.

1. After the critical frequency is determined, the values of *R* and C are selected to satisfy Equation (2.18). In principle, any values of *R* and *C* can be employed that will satisfy this critical frequency equation. A number of practical issues limit the selection, however. Some of these are:

   a. Very small values of resistance are to be avoided because they can lead to large currents, and thus large loading effects. Similarly, very large capacitance should be avoided. In general, we try to keep the resistance in the kΩ and above range, and capacitors in the μF or less range.

   b. Often, the exact critical frequency is not important, so that fixed resistors and capacitors of approximately the computed values can he employed. If exact values are necessary, it is usually easier to select and measure a capacitor, then compute and obtain the appropriate resistance using a trimmer resistance.

2. The effective input impedance and output impedance of the *RC* filter may have an effect on the circuit in which it is used because of loading effects. If the input impedance of the circuit being fed by the filter is low, you may want to place a voltage follower between the filter output and the next stage. Similarly, if the output impedance of the feeding stage to the filter is high. You may want to isolate the input of the filter with a voltage follower.

3. It is possible to cascade *RC* filters in series to obtain improved sharpness of the filter cutoff frequency. However, it is important to consider the loading of one *RC* stage by another. The output impedance of the first-stage filter must be much less than the input impedance of the next stage to avoid loading.

Apart from loading, cascading filters raises the filter equation by a power of the number cascaded. Thus, two high-pass filters of the same critical frequency would respond by Equation (2.20) squared.

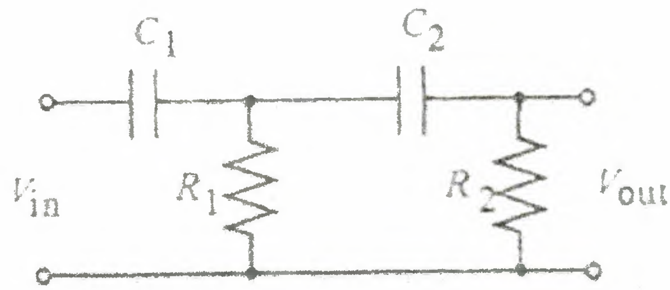


Figure 2.20 Cascaded high-pass filter

4. It is possible to place high-pass and low-pass filters together to realize a filter that passes only a fixed range of frequencies, that is. A band-pass filter. Conversely, it is possible to connect high- and low-pass filters together to obtain band-reject filter. In either case. The problem of loading of one stage by another must be considered.

2.4 Operational Amplifier

Early operational amplifier (op-amps) was used primarily to perform mathematical operation such as addition, subtraction, integration and differentiation, hence the term operational. These early devices were constructed with vacuum tubes and worked with high voltage. Today's op-amps are liner integrated circuits that use relatively low supply voltage and are reliable and inexpensive.

2.4.1 Symbol And Terminals

The standard op-amp symbol is shown in figure 2.21. IT has tow input terminals called the inverting input (-) and the non-inverting input (+), and one out put terminal.

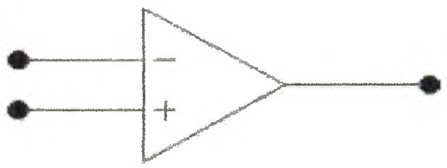


Figure 2.21 Op-amp symbol

The typical op-amp operates with tow dc supply voltage, one positive and the other negative, as shown in figure 2.22. Usually these dc voltage terminals are left off the schematic symbol for simplicity but are always understood to be there.

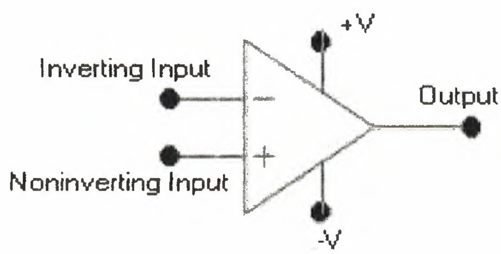


Figure 2.22 symbol with power connection.

2.4.2 Basic Operational Amplifier

Amplifiers (op-amp) are used primarily to perform mathematical operations such as addition, subtraction, integration, differentiation, as its name is operational. But now op-amps are linear integrated circuits that use relatively low supply voltages. There are four basic main operations of an operational amplifier.

- Comparators Amplifier.
- Summing Amplifier.
- The Integrator Amplifier.
- The Differentiator Amplifier.
- The Instrumental Amplifier.

2.4.2.1 Comparators

Operation Amplifiers are often used as nonlinear devices to compare the amplitude of one voltage with another. In this application, the op-amp is used in open-loop configuration; with the input voltage on one input and a reference voltage on the other e.g. it is used as over temperature sensing also used as analog to digital conversions.

Zero-Level Detection

The basic application of the op-amp as a comparator is in determining when an input voltage exceeds the certain level. Figure 2.23 shows a zero-level detector. The inverting (-) input is grounded and the input signal voltage is applied to non-inverting (+) input. Because of the high open-loop voltage gain, a very small difference voltage between the two inputs drives the amplifier into saturation, causing the output voltage to go its limit. For example, an op-amp have A_{out}=100,000. A voltage difference of 0.25mA between the input could produce an output voltage of (0.25mA) (100,000) =25V if the op-amp were capable. However, since most op-amp have output voltage limitation of less than $\pm$15V, the device would be driven into saturation.

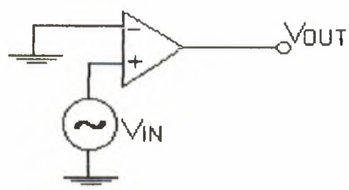


Figure 2.23 The Op-amp as zero-level Detector

Figure 2.24 shows sine wave input voltage applied to the non-inverting input of the zero-level detector. When sine wave is negative, the output is at its maximum negative level. When the sine wave cross 0, the amplifier is driven to it's opposite state and output goes to its maximum positive level. The zero-level detector can also be used to produce a square wave from sine wave.

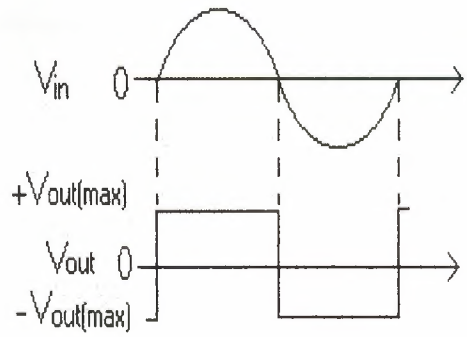


Figure 2.24 Output of zero-level detector

Nonzero-Level Detection

Op-amp can also be used to detect voltages other than zero by connecting a fixed reference voltage as shown in figure 2.25(a).

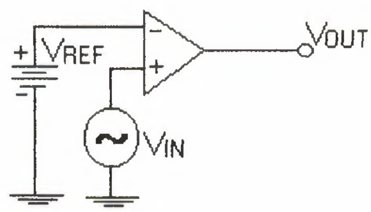


Figure 2.25 (a) Battery reference Nonzero-level Detector

A more practical example is shown in figure 2.25 (b) using a voltage divider to set reference voltage as follows:

$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V) \qquad (2.21)$$

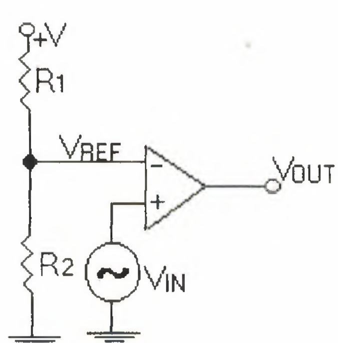


Figure 2.25 (b) Voltage divider Reference

Where +V is the positive op-amp supply voltage. We can also use zener voltage as a reference voltage $(V_Z = R_F)$ by applying a zener diode with the same circuit as shown in figure 2.25 (c).

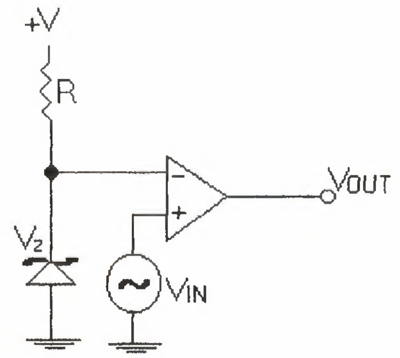


Figure 2.25 (c) Zener Diode sets reference voltage

As long as the input voltage V_{IN} is less than V_{REF}, the output remains at the maximum negative level. When the input voltage exceeds the reference voltage, the output goes to its maximum positive state as shown in figure 2.25(d) with a sine wave as input voltage.

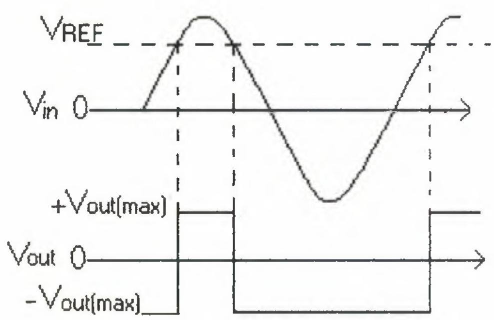


Figure 2.25(d) Output of Nonzero-level Detector

Out Bounding

In some applications, it is necessary to limit the output voltage levels of a comparator to a value less than that provided by the saturated op-amp. A single zener diode can be used as shown in the figure 2.26(a) to limit the output voltage swing to the zener voltage in one direction and to the forward diode drop in the other. This process of limiting the output voltage is called bounding.

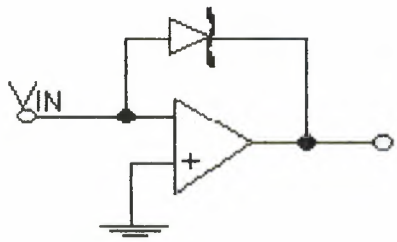


Figure 2.26 (a) Comparator with output bounding

Since the anode of zener is connected to the inverting input, it is at virtual ground$(V \approx 0)$. Therefore, when the output reaches a positive value equal to zener voltage, it limits at that value. When the output switches negative, the zener acts as regular diode and becomes forward biased at 0.7V, limiting the negative output swing to this value, as shown in figure 2.26 (b). Turning the zener around limits the output in opposite direction as shown in figure 2.26(c).

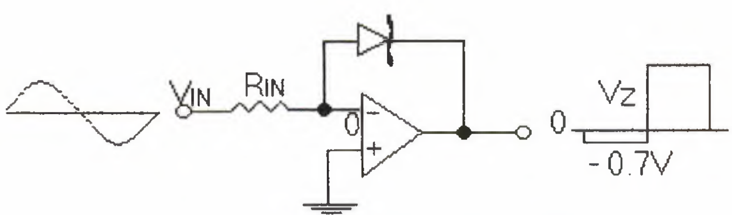


Figure 2.26 (b) Bounded at positive value

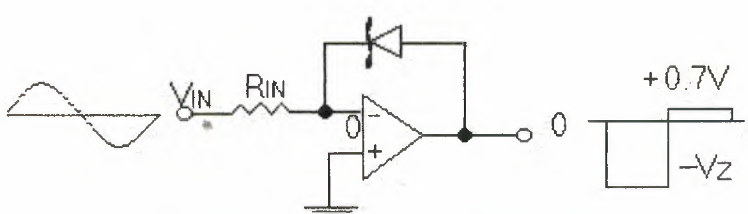


Figure 2.26 (c) Bounded at negative value

Two zener diodes arranged in figure 2.26(d) limit the output voltage to the zener voltage plus the voltage drop (0.7 V) of the forward biased zener, both positively and negatively as shown.

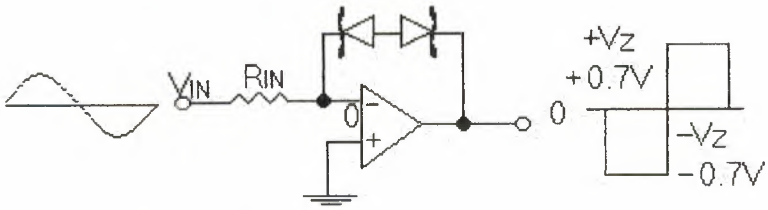


Figure 2.26 (d) Double bounded comparator

Window Comparator

Two comparators as in figure 2.27 (a) form a window comparator. This is used to detect input voltage between two limits, an upper and lower, called the "window". The upper and lower limits are set by reference voltages designated V_U and V_L. As long as the input voltage V_{IN} is within these two limits. The output of each comparator is at its low saturated level. Both diodes are reverse biased making V_{OUT} zero. When input goes above V_U and V_L, the output of that comparator goes to its saturated level.

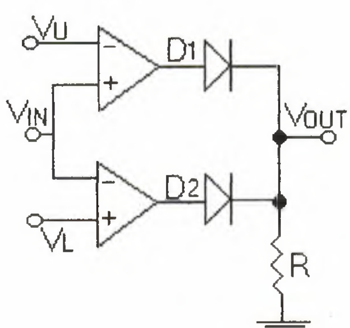


Figure 2.27 (a) A basic window Comparator

This action forward biased and produces a high level V_{OUT} illustrated in figure 2.27 (b) with V_{IN} changing arbitrarily.

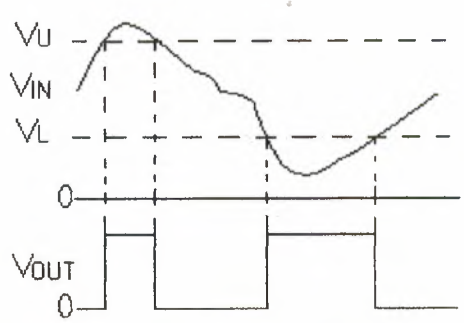


Figure 2.27 (b) Output of window comparator operation

2.4.2.2 Summing Amplifier

The summing amplifier is a variation of the inverting op-amp configuration. It is two or more inputs and its output voltage is proportional to the negative of the algebraic sum of its input voltages.

An n-input summing amplifier is shown in figure 2.28 (a). It operates like n inputs (V_{IN1}, V_{IN2},.........V_{INn}) are applied at its input and produce current (I_1, I_2.....I_n). The inverting input of the op-amp is almost 0 V, and there is no current into the input. This means that all inputs currents come together at this summing point and from the total current, which goes through R*f*, as indicated.

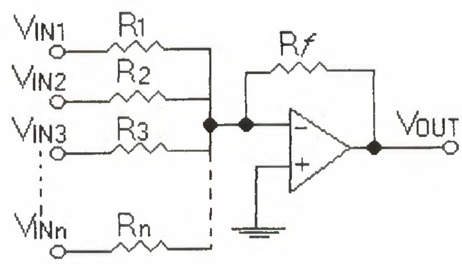


Figure 2.28 (a) Summing Amplifier with n inputs

$$I_T=I_1+I_2+........+I_n \qquad (2.22)$$

Since $V_{OUT} = -I_T Rf$

$$V_{OUT} = -(I_1+I_2+........+I_n)Rf \qquad (2.23)$$

$$V_{OUT} = -\left(\frac{V_{IN1}}{R_1}+\frac{V_{IN2}}{R_2}+........+\frac{V_{IN}n}{Rn}\right)Rf \qquad (2.24)$$

If all the resistances are of the same value that is R ($Rf=R_1=R_2=R_n$), then

$$V_{OUT} = -\left(\frac{V_{IN1}}{R}+\frac{V_{IN2}}{R}+........+\frac{V_{IN}n}{R}\right)R \qquad (2.25)$$

$$V_{OUT} = -(V_{IN1}+V_{IN2}+........+V_{IN}n) \qquad (2.26)$$

When R*f* is larger than the input resistors, the amplifier has a gain factor *Rf/R*, where R is the value of the each input resistor then Expression will be.

$$V_{OUT} = -\frac{Rf}{R}\left(V_{IN1} + V_{IN2} + \dots\dots + V_{IN}n\right) \qquad (2.27)$$

The output is the sum of all the voltages multiplied by the ratio *Rf/R* so it has gain greater than unity.

Averaging Amplifier

Summing amplifier can also be used to produce the mathematical average of the input voltages. This is done by setting the ratio *Rf/R* equal to the reciprocal of the numbers of the inputs. Normally we find average by dividing the sum all the elements by the total number of items. E.g. The output voltage is

$$V_{OUT} = -\frac{Rf}{R}\left(V_{IN1} + V_{IN2} + \dots\dots + V_{IN}n\right) \qquad (2.28)$$

$$V_{OUT} = -\frac{25K\Omega}{100K\Omega}\left(1V + 2V + 3V + 4V\right)$$

$$V_{OUT} = -2.5$$

It can easily be shown that the average of the input values is

$$\frac{1V + 2V + 3V + 4V}{4} = \frac{10V}{4} = 2.5$$

Scaling Adder

A different weight can be assigned to each input of the summing amplifier by simply Adjusting the values of the input transistors. Output voltages can be expressed as.

$$V_{OUT} = -\left(\frac{Rf}{R_1}V_{IN1} + \frac{Rf}{R_2}V_{IN2} + \dots\dots + \frac{Rf}{R_n}V_{IN}n\right) \qquad (2.29)$$

The weight of the particular input is set by the ratio of the *Rf* to the input resistance. For example, if an input voltage is to have a weight of 1 then $R = Rf$. Or, if weight of 0.5 is requires, $R = 2Rf$. The smaller the value of *R* the grater will be the weight and vice versa.

We can calculate weight of input voltages if R1 = 50KΩ, R2 = 100 KΩ, R3 = 10KΩ & Rf = 10 KΩ and V_{IN1} = +3V, V_{IN2} = +2V & V_{IN3} = +8V as shown in figure 2.29 then

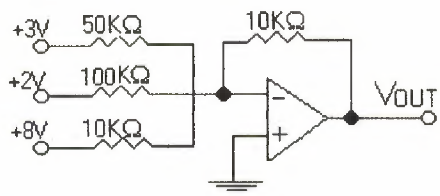


Figure 2.29 Labeled Diagram of scalar adder

Weight of input 1: $\frac{Rf}{R_1} = \frac{10K\Omega}{50K\Omega} = 0.2$

Weight of input 2: $\frac{Rf}{R_2} = \frac{10K\Omega}{100K\Omega} = 0.1$

Weight of input 3: $\frac{Rf}{R_3} = \frac{10K\Omega}{10K\Omega} = 1$

And V_{OUT} will be V_{OUT} = - [0.2(3V) + 0.1(2V) + 1(8V)]

= - (0.6V + 0.2V + 8V)

= - 8.8V

2.4.2.3 The Op-Amp Integrator

An op-amp integrator simulates mathematical integration, which is basically a summing process that determines the total area under the curve of a function. The basic integrator circuit is shown in the figure 2.30 (a). In this the feedback element is a capacitor that forms and *RC* circuit with the input resistor.

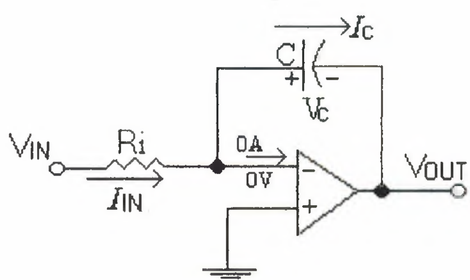


Figure 2. 30 (a) An op-amp Integrator with shown current

The expression for capacitor voltage is $Vc = \left(\frac{Ic}{C}\right)t$. As this expression is a straight-line beginning at zero with a constant slope of Ic/C and from algebra equation for straight line is $y = mx + b$. In this case $y = Vc, m= Ic/C, x = t, and\ b = 0.$

Capacitor voltage in a simple *RC* circuit is not linear but exponential. This is because of the charging current continuously decreases as the capacitor charges and cause the rate of change of voltage to continuously decrease. The key thing about using an op-amp with an *RC* circuit to form an integrator is that the capacitor's charging current is made constant, thus producing a straight-line (linear) voltage rather than an exponential voltage.

In the figure 2.30 (b) the inverting input of the op-amp is at ground (0 V), so that voltage across *Ri* equals V_{IN}. As

$$I_{IN} = \frac{V_{IN}}{R_i}$$

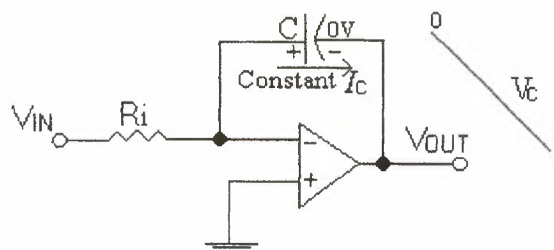


Figure 2.30 (b) A linear ramp voltage is produces across C

If V_{IN} is the constant voltage, then I_{IN} is also a constant because the inverting input always remains zero volts. Because of the very high impedance of the op-amp, there is negligible current into the inverting input. This makes all the current flow through the capacitor.

$$I_C = I_{IN}$$

Since I_C & I_{IN} are constants, so I_C charges the capacitor linearly and produces a linear voltage across *C*. the positive side of the capacitor is held at 0 V by the virtual ground of the op-amp. The voltage on the negative side of the capacitor decreases linearly from zero as the capacitor charges this voltage is called negative ramp. V_{OUT} is same as the voltage on the negative side of the capacitor. When the constant input voltage is in the form of the pulse is applied, the output ramp decreases negatively until the op-amp saturates at its maximum negative level as shown in figure 2.30 (c) pulse is applied, the output ramp decreases negatively until the op-amp saturates at its maximum negative level as shown in figure 2.30 (c)

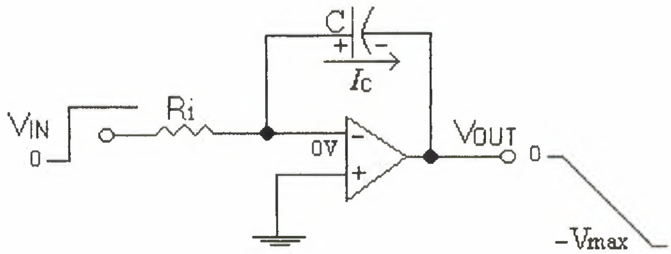


Figure 2. 30 (c) Constant V_{IN} produces as ramp on output

The rate, at which the capacitor charges, and therefore the slope of the output ramp are set, is set by the ratio Ic/C, as u has seen. Since $I_C = V_{IN}/R_i$, the rate of change or slope of the integrator's output voltage is

$$\frac{\Delta V_{OUT}}{\Delta t} = -\frac{V_{IN}}{R_i C} \qquad (2.30)$$

Integrators are especially useful in triangular-wave generator.

2.4.2.4 The Op-amp Differentiator

An op-amp differentiator simulates mathematical differentiation, which is a process of determining the instantaneous rate of change of the function. The basic differentiator is shown in the figure 2.31(a). Notice how the placement of the capacitor and resistor from the integrator is capacitor is now at the input and resister is used as a feed back. The differentiator produces an output that is proportional to the rate of change of the input voltage.

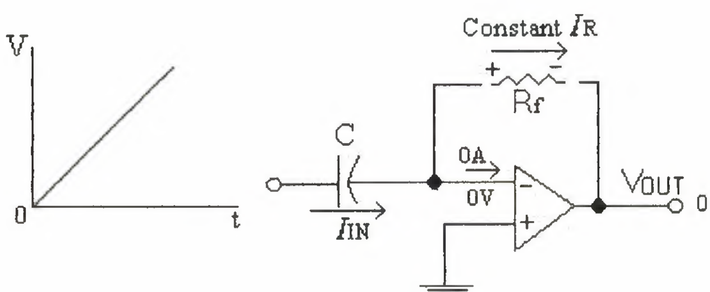


Figure 2. 31 (a) A differentiator with ramp input

We apply a positive-going ramp voltage to the input making $I_C = I_{IN}$ and voltage across the capacitor is equal to V_{IN} at all times because of virtual ground on the inverting input from the basic formula, $V_C = \left({}^{I_C}\!/_{C} \right) t$, we get:

$$I_C = \left(\frac{V_C}{t} \right) C \qquad (2.31)$$

Since the current into the inverting input is negligible, $I_R = I_C$. Both current are constant because the slope of the capacitor voltage (V_C / t) is constant. The output voltage is also constant and equals to the voltage across Rf because one side of the feedback resistor is always 0 V.

$$V_{OUT} = I_R Rf = I_C Rf \qquad (2.32)$$

$$V_{OUT} = \left(\frac{V_C}{t} \right) RfC \qquad (2.33)$$

The output is negative when the input is a positive-going ramp and positive when the input is a negative-going ramp as shown in figure 2.31(b). During the positive slope of the input, the capacitor is charging from the input source and the constant current through the feedback resistor is in direction. During the negative slope of the input, the current is in opposite direction because the capacitor is discharging.

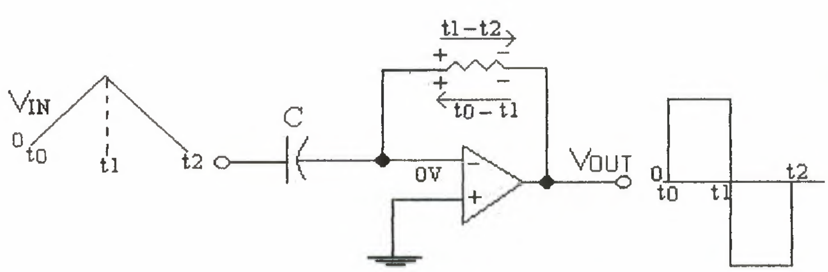


Figure 2. 31 (b) Output with a series of positive and negative ramps on input

As from the equation $V_{OUT} = \left(\frac{V_C}{t}\right) RfC$, term V_C / t is the slope of the input. If the slope increases, V_{OUT} increases. If the slope decreases, V_{OUT} decreases. So, the output voltage is proportional to the slope (rate of change) of the input. The constant of proportionality is the time constant, *RfC*.

2.4.2.5 The Instrumental Amplifier

Instrumental amplifier consists of three op-amp and several resistors. IC manufacturers provide this circuit in a package as one device. Common characteristics are high input resistance, high voltage gain and excellent common-mode rejection ratio. Instrumental amplifiers are commonly used in data acquisitions systems where remote sensing of input variable is required.

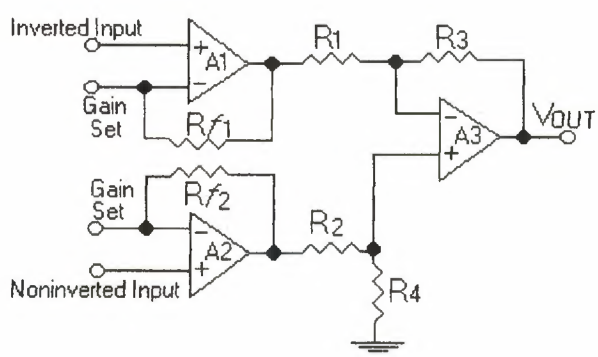


Figure 2. 32 (a) Basic Instrumentation Amplifier

A simple instrumental amplifier is shown in figure 2.32(a). Op-amps A_1 and A_2 are non-inverting amplifier stage that provides high input impedance and voltage gain. Op-amp A_3 is a unity gain amplifier. When R_G is connected externally as shown in figure 2.32(b) op-amp receives a differential input signal V_{IN1} on its non-inverting input and amplifies it with a gain of $1 + R_{f1}/R_G$. Op-amp A_1 also receives an input signal V_{IN2} through A_2, R_{f2} and R_G. V_{IN2} appears on the inverting input of op-amp A_1 and is amplified by a gain of R_{f1}/R_G . Also the common-mode voltage on the non-inverting is amplified by the common mode of A_1. (V_{cm} is typically less then unity) The total input voltage of op-amp is as follows.

$$V_{OUT1} = \left(1 + \frac{R_{f1}}{R_G}\right)V_{IN1} - \left(\frac{R_{f1}}{R_G}\right)V_{IN2} + V_{cm} \qquad (2.34)$$

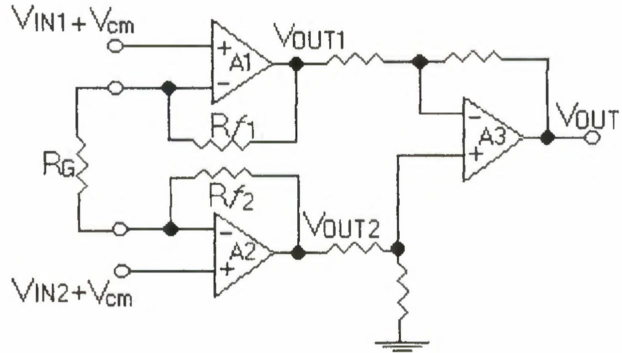


Figure 2. 32 (b) Instrumentation amplifier with Gain resistor set

A similar analysis can be applied to op-amp A_2, as shown below

$$V_{OUT2} = \left(1 + \frac{R_{f2}}{R_G}\right)V_{IN2} - \left(\frac{R_{f2}}{R_G}\right)V_{IN1} + V_{cm} \qquad (2.35)$$

The differential voltage to the op-amp A_3 is V_{OUT2}- V_{OUT1}

$$V_{OUT2} - V_{OUT1} = \left(1 + \frac{R_{f2}}{R_G} + \frac{R_{f1}}{R_G}\right)V_{IN2} - \left(\frac{R_{f2}}{R_G} + 1 + \frac{R_{f1}}{R_G}\right)V_{IN1} + V_{cm} - V_{cm} \qquad (2.36)$$

For $R_{f2} = R_{f1} = R_f$

$$V_{OUT2} - V_{OUT1} = \left(1 + \frac{2R_f}{R_G}\right)V_{IN2} - \left(1 + \frac{2R_f}{R_G}\right)V_{IN1} + V_{cm} - V_{cm} \qquad (2.37)$$

Since the common-mode voltage (V_{cm}) are equal, they cancel out. Factoring gives the following result, which is differential input to op-amp A_3

$$V_{OUT2} - V_{OUT1} = \left(1 + \frac{2R_f}{R_G}\right)(V_{IN2} - V_{IN1}) \qquad (2.38)$$

Because op-amp A_3 has unity gain, the final output of the instrumental amplifier is $V_{OUT} = (1)(V_{OUT2} - V_{OUT2})$

$$V_{OUT} = \left(1 + \frac{2R_f}{R_G}\right)(V_{IN2} - V_{IN1}) \qquad (2.39)$$

The close loop gain is

$$A_{CL} = 1 + \frac{2R_f}{R_G}$$

This equation shows the differential gain of the instrumentation amplifier can be set by value R_G. R_{f1} and R_{f2} are internal to the IC chip and manufacturer sets their values.

The instrumental amplifier is normally used to measure differential signal voltage that is superimposed on a common-mode voltage often larger than the signal voltage. Applications often include a situation where a quantity is measured by remote sensing device (transducer), and resulting small electrical signal is sent over a long line subject to large common-mode voltages. Instrumental amplifier at the end of the line must amplify the small signal and reject the large common mode voltage as shown in Figure 2.32(c).

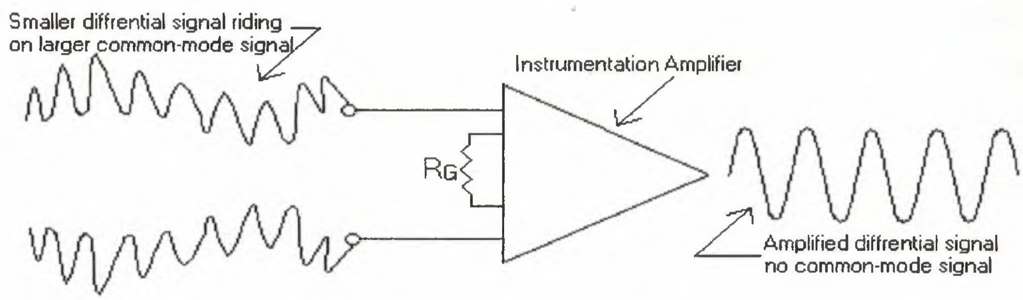


Figure 2. 32 (c) Showing rejection of large common-mode signal

2.5 Protection

There are many situations where the connection of a sensor to the next unit, e.g. a microprocessor, can lead to the possibility of damage as a result of perhaps a high current or high voltage. A high current can be protected against by the incorporation in the input line of a series resistor to limit the current to an acceptable level and a fuse to break if the current does exceed a safe level.

High voltages, and wrong polarity, may be protected against by the use of a Zener diode circuit figure 2.33 Zener diodes behave like ordinary diodes up to some breakdown voltage when they become conducting. Thus to allow a maximum voltage of 5V but stop voltages above 5.1V getting through, a Zener diode with a voltage rating of 5.1V might be chosen. When the voltage rises to 5.1V the Zener diode breakdown and its resistance drops to a very low value. The result is that the voltage across the diode, and hence that outputted to the next circuit, drops. Because the Zener diode is a diode with a low resistance for current in one direction through it and a high resistance for the opposite direction, it also provides protection against wrong polarity.

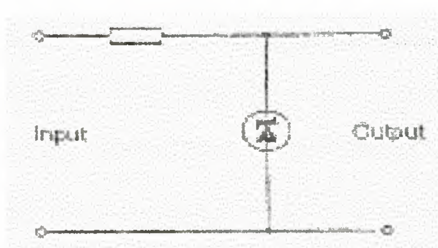


Figure 2.33 Zener diode protection circuit

In some situations it is desirable to completely isolate circuits and remove all electrical connections between them. This can be done using an *optoisolator.* This involves converting an electrical signal into an optical signal, then passing it to a detector which then converts it back into an electrical signal figure 2.34 The input signal is fed through an infrared light emitting diode (LED). The infrared signal is then detected by a phototransistor. To prevent the LED having the wrong polarity or too high an applied voltage, it is likely to be protected by the Zener diode circuit shown in figure 3.10. Also. If there were alternating signal in the input a diode would be put in the input line to rectify it. Optoisolators are widely used with programmable logic controllers at this input/output ports to protect the microprocessors from damage.

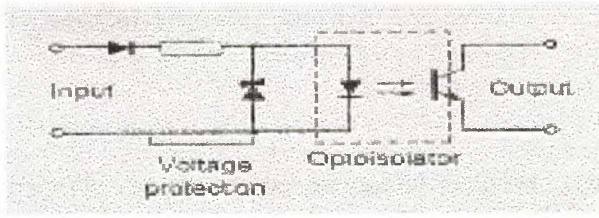


Figure 2.34 Optoisolator

2.6 Design Guidelines

This section discusses typical issues that should be considered when designing an analog signal-conditioning system. The examples show how the guidelines can be used to develop a design. The guidelines ensure that the problem is clearly understood and that the important issues are included.

Not every guideline will be important in every design, so some will not be applicable. In many cases, not enough information will be available to address an issue properly: then the designer must exercise good technical judgment in accounting for that part of the design.

Figure 2.35 shows the measurement and signal-conditioning model. In some cases the entire system is to be developed from selecting the sensor to designing the signal conditioning. In other cases, only the signal conditioning will be developed. The guidelines are generalized. Since the sensor is selected from what is available, the actual design is really for the signal conditioning.

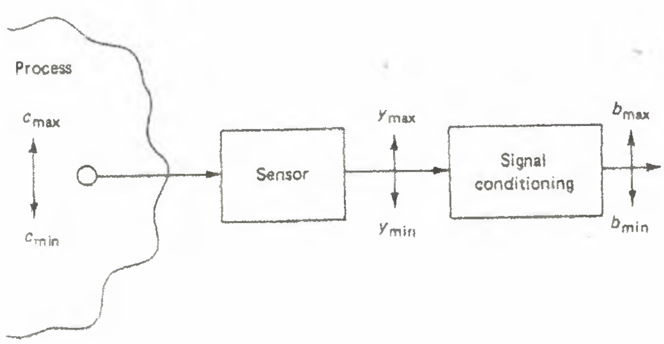


Figure 2.35 Model for measurement and signal-conditioning objectives.

Guidelines for Analog Signal Conditioning Design

1. Define the measurement objective.

a. Parameter: What is the nature of the measured variable: pressure, temperature, flow, level, voltage, current, resistance, etc.?

b. Range: What is the range of the measurement: 100 to 200°C, 45 to 85 psi. 2 to 4 V?

c. Accuracy: What is the required accuracy: 5% FS, 3% of reading, etc.?

d. Linearity: Must the measurement output be linear?

e. Noise: What is the noise level and frequency spectrum of the measurement environment?

2. Select a sensor (if applicable).

a. Parameter: What is the nature of the sensor output: resistance, voltage. etc.?

b. Transfer function: What is the relationship between the sensor output and the measured variable: linear, graphical, equation, accuracy, etc.?

c. Time response: What is the time response of the sensor: first-order time constant, second-order damping, and frequency?

d. Range: What is the range of sensor parameter output for the given measurment range?

e. Power: What is the power specification of the sensor: resistive dissipation maximum, current draw. etc.?

3. Design the analog signal conditioning (S/C).

a. Parameter: What is the nature of the desired output? The most common is voltage, but current and frequency are sometimes specified. In the latter cases. Conversion to voltage is still often a first step.

b. Range: What is the desired range of the output parameter (e.g., 0 to 5 V, 4 to 20mA, 5 to 10 kHz)?

c. Input impedance: What input impedance should the S/C present to the input signal source? This is very important in preventing loading of a voltage signal input.

d. Output impedance: What output impedance should the S/D coffer to the output load circuit?

4. Notes on analog signal conditioning design.

a. If the input is a resistance change and a bridge or divider must be used, be sure to consider both the effect of output voltage nonlinearity with resistance and the effect of current through the resistive sensor.

b. For the op amp portion of the design, the easiest design approach is to develop an equation for output versus input. From this equation, it will be clear what types of circuits may be used. This equation represents the static transfer function of the signal conditioning.

c. Always consider any possible loading of voltage sources by the signal conditioning. Such loading is a direct error in the measurement system.

3.DIGITAL SIGNSL CONDITIONING ELEMENTS

3.1 INTRODUCTION

Perhaps the best way to start this chapter is to consider briefly why we are interested in digital signal conditioning. An overall survey of electronics applications in industry shows that conversions to digital techniques are occurring rapidly. There are many reasons for this conversion, but two in particular are important. One is the reduction in uncertainty when dealing with digitally encoded information, compared with analog information. Note that we said uncertainly, not accuracy. If a system presents analog information, great care must be taken to account for electrical noise influence.

Drift of amplifier gains, loading effects, and a host of other problems familiar to the analog electronics designer. In a digitally encoded signal, however, a wire carries either a high or low level and is not particularly susceptible to the problems associated with analog processing. Thus, there is an inherent certainty in representing information by digital encoding because of the isolation of digital representation from spurious influences. The accuracy of this signal in representing the information is discussed in Section 3.3.

A second reason for conversion to digital electronics is the growing desire to use digital computers in the industrial process. The digital computer, by nature, requires information to be encoded in digital format before it can be used. The need for digital signal conditioning thus becomes a question of why computers are so widely used in industry. As discussed, a few reasons are:

1. A computer easily controls a multivariable process-control system.
2. Through computer programming, nonlinearities in a sensor output can be linearized.
3. Complicated control equations can be solved to determine required control functions.
4. Computers have the ability to microminiaturize complex digital processing circuits as integrated circuits (ICs).

Finally, the development of microprocessors has brought about a transformation of process control to digitally based control systems. With microprocessor-based computers, implementation of computer-based control systems has become practical, and with it, the need for knowledge of digital signal conditioning. This technology reduces not only physical size but also both power consumption and failure rate.

With the growing use of computers in process-control technology, it is clear that any individual trained to work in this field also must be versed in the technology of digital electronics. But how far should such preparation extend into this related complex field of study. The answer is that a process-control technologist must understand the elements and characteristics of process-control loops. In this context, digital electronics is used as a tool to implement necessary features of process control, and therefore the technician should understand how such devices affect the characteristics of the loop. Consider that one does not need to know detailed physics of stretched wires to understand the application of strain gauges and use these devices successfully in process control. Similarly, one does not need to know the internal design of logic gates and microcomputers to use such devices in process control. Thus the objectives of this chapter have been carefully chosen to provide the reader with sufficient background in digital technology to understand its application to process control.

3.2 REVIEW OF DIGITAL FUNDAMENTALS

A working understanding of the application of digital techniques to process control requires a foundation of basic digital electronics. The design and implementation of control logic systems and microcomputer control systems require a depth of understanding that can be obtained only by taking several courses devoted to the subject. In this text. we assume a sufficient background that the reader can appreciate the essential features of digital electronic design and its application to process control.

3.2.1 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 of voltage on a wire. We speak, then. of the digital information as a high state (H or 1) or a low state (L or 0) on a wire that carries the digital signal.

Digital Words Given the simple binary information that is carried by a digital signal, it is clear that a more complicated arrangement must be used to describe analog information. Generally, this is done by using an assemblage of digital levels to construct a word. 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 **101011_2,** which can be thought of as a 6-digit base 2 number. An important consideration, then, is how the process-control information is encoded into this digital word.

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 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, Octal numbers are conveniently formed from groupings of three binary digits: that is. 000_2; is 0_8 and 111_2; is 7_8, Thus. a binary number like 101011_2; is equivalent to 53_8. Hex numbers are formed easily from groupings of four binary digits: that is, 0000_2; is 0H and 1111_2; is FH. The capital H is used to designate a hex number instead of a subscript 16. Also recall that the hex counting sequence is 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, and F to cover the possible states. Because microcomputers must frequently use either 4-bit, 8-bit. Or 16-bit words, the hex notation are commonly used with these machines. In hex, a binary number like 10110110_2 would be written B6H.

3.2.2 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. Such numbers, just as in the decimal framework, represent divisions of the counting system to values less than unity. A correlation can be made to decimal numbers in a similar fashion to binary Equation, as

$$N_{10} = b_1 2^{-1} + b_2 2^{-2} + \cdots b_m 2^{-m}$$

where N_{10} = base 10 number less than one

$b_1 b_2 \ldots b_{m-1} b_m$ = base 2 number less than one, m =number of digits in base 2 number.

Conversion of a base 10 number that is less than I to a binary equivalent employs a procedure where repeated multiplication by 2 is performed. The result of each multiplication will be a fractional part and either a 0 or 1 whole number part. Which determines whether that digit is a 0 or 1. The first multiplication gives the most significant bit b1. And the last gives either a 0 or 1 for the least significant bit b_m.

3.2.3 Boolean Algebra

In process control, as well as in many other technical disciplines, action is taken on the basis of an evaluation of observations made in the environment. In driving an automobile, for example, we are constantly observing such external factors as traffic, lights, speed limits, pedestrians, street conditions, low-flying aircraft, and such internal factors as how fast we wish to go. Where we are going, and many others. We evaluate these factors and take actions predicated on the evaluations. We may see that a light is green, streets dry, speed low, no pedestrians or aircraft, we are late. And thus conclude that an action of pressing on the accelerator is required. Then we may observe a parked police radar unit with all other factors the same, negate the aforementioned conclusion, and apply the brake. Many of these parameters can be represented by a *true* or *not true* observation: in fact, with enough definition, all the observations could be reduced to simple true or false conditions. When we learn to drive, we are actually setting up internal responses to a set of such true/false observations in the environment.

In the industrial world, an analogous condition exists relative to the external and internal influences on a manufacturing process, and when we control a process we are in effect teaching a control system response to a set of true/false observations. This teaching may consist of designing electronic circuits that can logically evaluate the set of true/false conditions and initiate some appropriate action. To design such an electronic system, we must first be able to mathematically express the inputs, the logical evaluation, and the corresponding outputs. *Boolean algebra* is a mathematical procedure that allows the combinations of true/false conditions in various logical operations by equations so that conclusions can be drawn. For purposes of this text. We do not require expertise in Boolean technique, but an operational familiarity with it that can be applied to a process-control environment.

Before a particular problem in industry can be addressed using digital electronics. It must be analyzed in terms that are amenable to the binary nature of digital techniques. Generally, this is accomplished by staling the problem in the form of a set of true/false-type conditions that must be applied to derive some desired result. These sets of conditions then are stated in the form of one or more Boolean equations. We will see in Section 3.2.4 that a Boolean equation is in a form that is readily implemented with existing digital circuits. The mathematical approach of Boolean algebra allows us to write an analytical expression to represent these stipulations.

Let us consider a simple example of how a Boolean equation may result from a practical problem. Consider a mixing tank for which there are three variables of interest: liquid level, pressure, and temperature. The problem is that we must signal an alarm when certain combinations of conditions occur among these variables. Referring to Figure 3.1. we denote level by A. pressure by B. and temperature by C. and assume that setpoint values have been assigned for each variable so that the Boolean variables are either 1 or 0 as the physical quantities are above or below the setpoint values. The alarm will be triggered when the Boolean variable D goes to the logic true state.

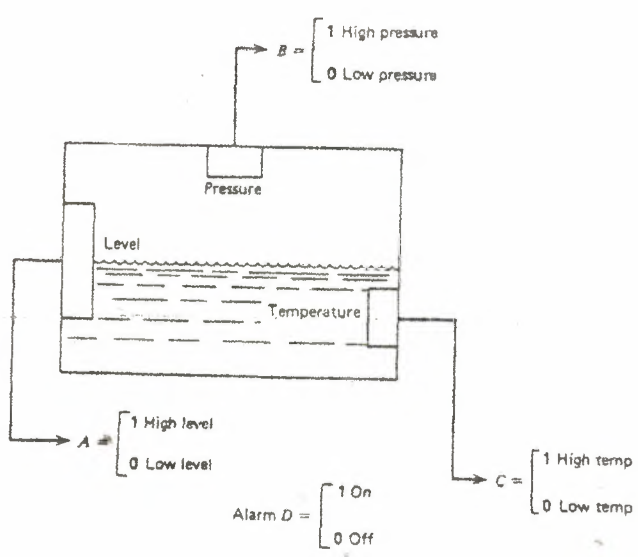


Figure 3.1 System for illustrating Boolean applications to control (section 3.2.3)

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

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

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

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 from the starting point for a design of electronic digital circuitry that would perform the indicated operations.

3.2.4 Digital Electronics

The electronic building blocks of digital electronics are designed to operate on the binary levels present on digital signal lines. These building blocks are based on families of types of electronic circuits, that have their specific stipulations of power supplies and voltage levels of the 1 and 0 states The basic structure involves the use of AND/OR logic and NAND/NOR logic to implement Boolean equations.

EXAMPLE

Develop a digital circuit using AND/OR gates that implements the equation developed in Section 3.2.3.

Solution

The problem posed in Section 3.2.3 (with Figure 3.1) has a Boolean equation solution of

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

The implementation of this equation using AND/OR gates is shown in Figure 3.2. The AND, OR. and inverter are used in a straightforward implementation of the equation.

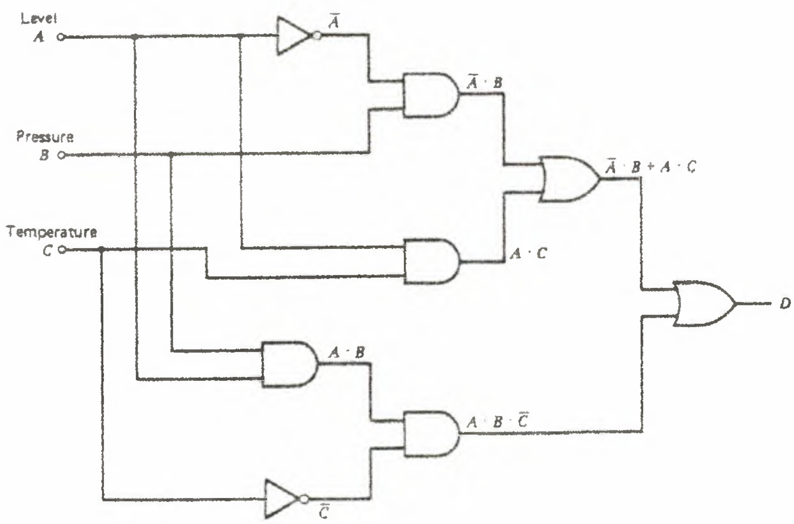


Figure 3.2 Solution for example

3.2.5 Programmable Logic Controllers

The move toward digital logic techniques and computers in industrial control paralleled the development of special controllers called programmable logic controllers (PLCs) or simply programmable controllers (PCs). These devices are particularly suited to the solution of control problems associated with Boolean equations and binary logic problems in general. They are a computer-based outgrowth of relay sequence controllers.

3.2.6 Computer Interface

Figure 3.3 shows a simple model of a computer system. The processor is connected to external equipment via three parallel sets of digital lines. The data lines carry data to and from the processor. The address lines allow the computer to select external locations for input and output. The control lines carry information to and from the computer related to operations such as reading, writing, interrupts, and so on. This collection of lines is called the bus of the computer.

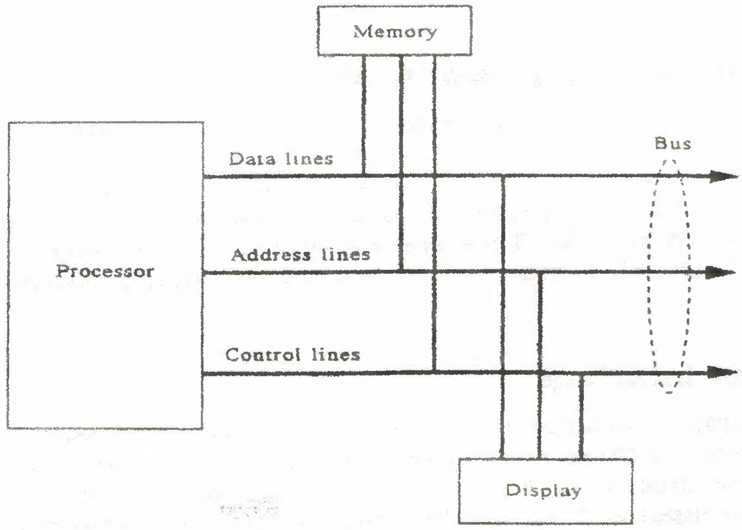


Figure 3.3 Generic model of a computer bus system

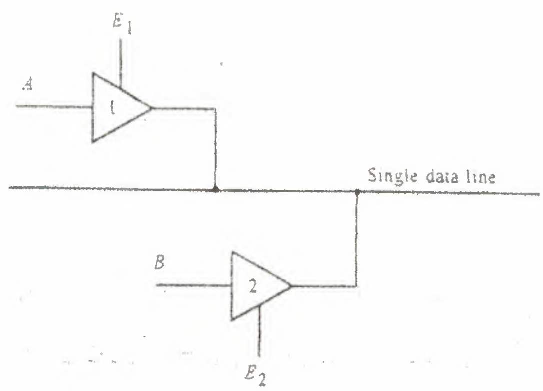


Figure 3.4 Tri-state buffers allow multiple signals to share a single digital line in the bus

The term *interface* refers to the hardware connections and software operations necessary to input and output data using connections to the bus. All of the equipment connected to the computer must share the bus lines.

It is an important consideration for interface hardware that a bus line not be compromised by some external connection. This means that the external equipment must not hold a bus line in a logic state when that equipment is not using the bus. If a data line is held at 0 by some equipment even when it is not performing data transfer, then no other equipment could raise that line to the 1 state during its data transfer operations. This problem is prevented by use of tri-state buffers.

Tri-State Buffers Isolation of a bus line is accomplished by making all connections via a special digital device called a tri-state buffer. This device acts like a simple switch. When the switch is closed, the logic level on its input is impressed upon the output. When open, the output is placed in a high impedance state that is, an open circuit.

Figure 3.4 shows how two digital signals can both be connected to a single data line through tri-state buffers. Normally, both tri-states are disabled, that is. In the high impedance state. When the computer needs to input signal *A,* an enable signal, E_1, is sent to tri-state 1 so that the state of *A* is placed on the data line. After the computer reads the line, tri-state 1 is disabled again. Similarly, when the computer needs the state of signal *B,* an enable, E_2, is sent to tri-state 2 to place *B* on the line.

3.3 BUFFERING

Frequently the signals reaching the inputs of a microprocessor are spasmodic. Sometimes the signals come in rapid bursts, which may be too fast for the microprocessor to accept. Sometimes the microprocessor is engaged in some other activity and cannot accept them at the time they arrive. The output from a microprocessor may be too fast for an actuator or other device, new data being transmitted to it before it has had time to accept the previous data. For these reasons, external storage is provided for signals. This is provided in what are termed buffers.

For a buffer on the input, data is transferred out of it at a rate determined by the microprocessor. For a buffer on the output, data is transferred out of it at a rate determined by the peripheral device being fed. The buffer memory fills and empties to compensate for the difference between the input rate of the data into the buffer and the required output rate. The ability of the buffer to cope is determined by the size if its memory and the difference in input and output transfer rates.

3.4 CONVERTERS

The most important digital tool for the process-control technologist is one the 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. To interface this signal with a compute or digital logic circuit, it is necessary first to perform an analog-to-digital (A/D) conversion. The specifics of this conversion must be well known so that a unique, known relationship exists between the analog and digital signals. Often, the reverse situation occurs, where a digital signal is required to drive an analog device. In this case. A digital-to-analog (D/A) converter is required.

3.4.1 Multiplexers

Frequently there is a need for measurements to be sampled from a number of different locations, or perhaps a number of different measurements need to be made. Rather than use a separate microprocessor for each measurement, a multiplexer can be used figure 3.5. The multiplexer is essentially a switching device, which enables each of the inputs to be sampled in turn.

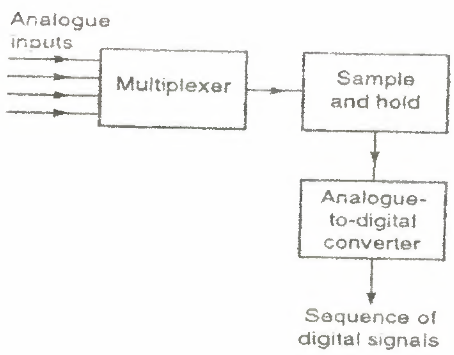


Figure 3.5 Analog to digital conversion using a multiplexer.

3.4.2 Comparators

The most elementary form of communication between the analog and digital is a device (usually an IC) called a comparator. This device, which is shown schematically in Figure 3.6, simply compares two analog voltages on its input terminals. Depending on which voltage is larger, the output will be a I (high) or a 0 (low) digital signal. The comparator is extensively used for alarm signals to computers or digital processing systems. This element also is an integral part of the analog-to-digital and digital-to-analog converter, to be discussed in Section 3.4.3.

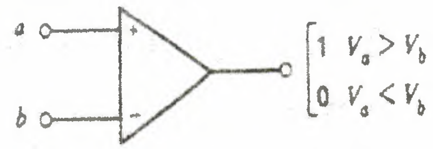


Figure 3.6 A basic comparator has an output digital logic state that depends on tow analog input voltages.

One of the voltages on the comparator inputs, *Va,* or *Vb,* in Figure 3.6, will be the variable input, and the other a fixed value called a trip, trigger, or reference voltage. The reference value is computed from the specifications of the problem and then applied to the appropriate comparator input terminal, as the following Example. The reference voltage is provided from a divider using available power supplies.

Example

A process-control system specifies that temperature should never exceed 160°C if the pressure also exceeds 10 Pa. Design an alarm system to detect this condition. using temperature and pressure transducers with transfer functions of 2.2 mV/C and 0.2 V/Pa, respectively.

Solution

The alarm conditions will be a temperature signal of (2.2 mV/°C)(160°C) = 0.352 V coincident with a pressure signal of (0.2 V/Pa)(10 Pa) = 2 volts. The circuit of Figure 3.7 shows how this alarm can be implemented with comparators and one AND gate. The reference voltages could be provided from dividers.

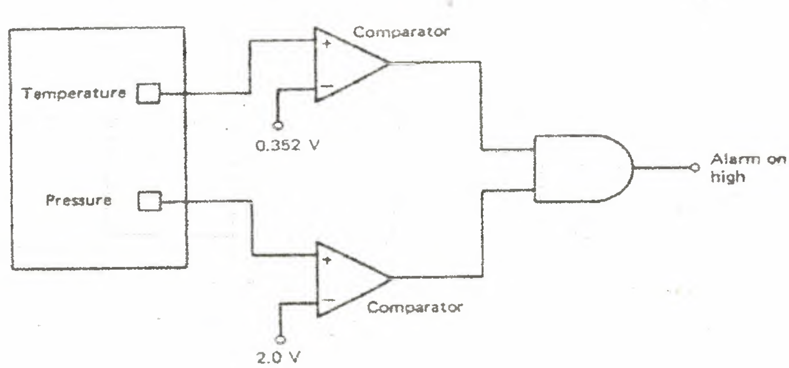


Figure 3.7 Diagram of a solution to Example

Hysteresis Comparator When using comparators, there is often a problem if the signal voltage has noise or approaches the reference value too slowly. The comparator output may "jiggle" back and forth between high and low as the reference level is reached. This effect is shown in Figure 3.8. Such fluctuation of output may cause problems with the equipment designed to interpret the comparator output signal.

This problem often can be solved by providing a *deadband* or *hysteresis* to the reference level around which output changes occur. Once the comparator has been triggered high. the reference level is automatically reduced so that the signal must fall to some value below the old reference before the comparator goes to the low state.

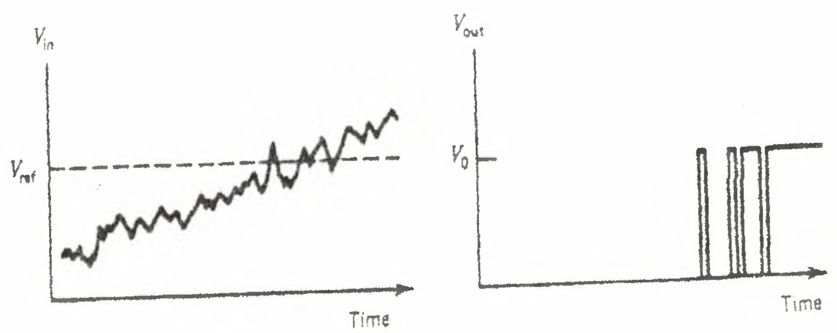


Figure 3.8 A comparator output will "jiggle" when a noisy signal passes through the reference voltage level.

There are many ways this hysteresis can be provided, but Figure 3.9a shows one common technique. Feedback resistor *Rf* is provided between the output and one of the inputs of the comparator, and that input is separated from the signal by another resistor, *R*. Under the condition that *Rf* >>*R*, the response of the comparator is shown in Figure 3.9b.

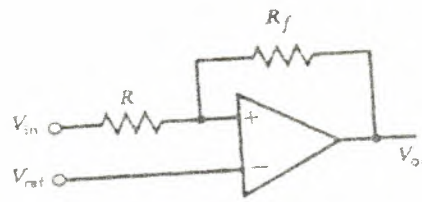
The condition for which the output will go high (*Vo)* is defined by the following condition:

$$V_{in} \geq V_{ref} \tag{3.1}$$

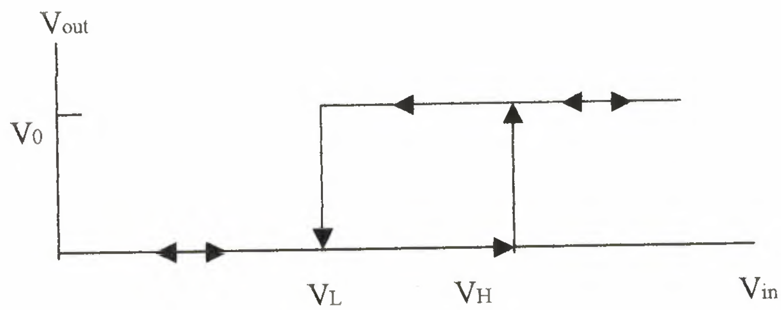
Once having been driven high. the condition for the output to drop back to the low (0 V) state is given by the relation:

$$V_{in} \leq V_{ref} - (R/R_f)V_0 \tag{3.2}$$

The dead band or hysteresis is given by $(R/R_f)V_0$, and is thus selectable by choice of the resistors, as long as this relation is satisfied. The response of this comparator is shown by the graph in Figure 3.9b. The arrows indicate increasing or decreasing input voltage.



(A)



(B)

Where, $V_{ref} = V_H,\ VL = V_{ref} - R / R_f * V_0$

Figure 3.9 A hysteresis comparator has an input voltage window within which output changes do not occur. This provides noise immunity.

3.4.3 Digital-to-Analog Converters (DACs)

A DAC 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. Especially when used in connection with a computer, this binary number is called a binary word or computer word. The digits are called bits of the word. Thus an 8-bit word would be a binary number having eight digits, such as $\mathbf{10110110_2}$. 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 numbel that the word represents as a fractional number. In this context, the output of the DAC can be defined using equation (3.3) as a scaling of some reference voltage.

$$V_{out} = V_R[b_1 2^{-1} + b_2 2^{-2} + \cdots b_n 2^{-n}] \qquad \textbf{(3.3)}$$

Where V_{out} = analog voltage output

V_R = reference voltage

$b_1, b_2, \ldots\ldots, b_n$ = n-bit binary word

The minimum V_{out} is zero, and the maximum is determined by the size of the binary word because, with all bits set to one, the decimal equivalent approaches Vg as the number of bits increases. Thus, a 4-bit word has a maximum of

$$V_{max} = V_R[2^{-1} + 2^{-2} + 2^{-3} + 2^{-4}] = 0.9375 V_R$$

and an 8-bit word has a maximum of

$$V_{max} = V_R[2^{-1} + 2^{-2} + 2^{-3} + 2^{-4} + 2^{-5} + 2^{-6} + 2^{-7} + 2^{-8}] = 0.9961 V_R$$

An alternative equation to Equation (3.3) is often easier to use. This is based on noting that the expression in brackets in Equation (3.3) is really just the fraction of total counting states possible with the n-bits being used. With this recognition, we can write:

$$V_{out} = \frac{N}{2^n} V_R \qquad \textbf{(3.4)}$$

Where N = base 10 whole number equivalent of DAC input

Suppose an 8-bit converter with a 5.0-volt reference has an input of **10100111_2,** or A7H. If this input is converted to base 10, we get N = 167_{10} and 2^8 = 256. From Equation (3.4), the output of the ADC will be:

$$V_{out} = \frac{167}{256} 5.0 = 3.2617 \text{ volts}$$

Bipolar DAC Some DACs are designed to output a voltage that ranges from plus to minus some maximum when the input binary ranges over the counting states. Although computers frequently use 2s complement to represent negative numbers, this is not common with DACs. Instead, a simple offset-binary is frequently used, wherein the output is simply biased by half the reference voltage of Equation (3.4). The bipolar DAC relationship is then given by:

$$V_{out} = \frac{N}{2^n} V_R - \frac{1}{2} V_R \tag{3.5}$$

Notice that if N = 0 the output voltage will be given by the minimum value. $V_{out}(min) = -VR/2$. However, the maximum value For N is equal to (2^n - 1), so that the maximum value of output voltage will be:

$$V_{out}(max) = \frac{(2^n - 1)}{2^n} V_R - \frac{1}{2} V_R = \frac{1}{2} V_R - \frac{V_R}{2^n} \tag{3.6}$$

DAC Characteristics For modern applications, most DACs are integrated circuit (IC) assemblies, viewed as a black box having certain input and output characteristics. In Figure 3.10, we see the essential elements of the DAC in terms of required input and output. The associated characteristics can be summarized by reference to this figure.

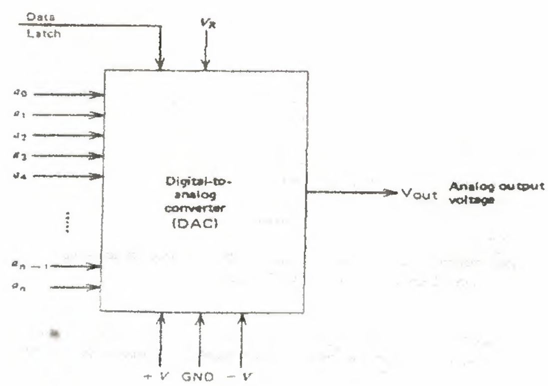


Figure 3.10 A generic DAC diagram, showing typical input and output signal.

1. ***Digital input*** Typically, a parallel binary word of a number of bits specified by the device specification sheet. Typically, TTL logic levels are required

2. ***Power supply*** This is bipolar at a level of ±12 to ±18 V as required for internal amplifiers. Some DACs operate from a single supply.

3. ***Reference supply*** Required to establish the range of output voltage and resolution of the converter. This must be a stable, low-ripple source. In some units, an internal reference is provided.

4. ***Output*** *A* voltage representing the digital input. This voltage changes in steps as the digital input changes by bits, with the step determined. The actual output may be bipolar if the converter is designed to interpret negative digital inputs.

5. ***Offset*** Because the DAC is usually implemented with op amps, there may be the typical output offset voltage with a zero input. Typically, connections will be provided to facilitate a zeroing of the DAC output with a zero word input.

6. ***Data latch*** Many DACs have a data latch built into their inputs. When a logic command is given to latch data, whatever data are on the input bus will be latched into the DAC and the analog output will be updated for that input data. The output will stay at that value until new digital data are latched into the input. In this way the input of the DAC can be connected directly onto the data bus of a computer, but it will be updated only when a latch command is given by the computer.

7. ***Conversion -time*** A DAC performs the conversion of digital input to analog output virtually instantaneously. From the moment that the digital signal is placed on the inputs to the presence of the analog output voltage is simply the propagation time of the signal through internal amplifiers. Typically, settling time of the internal amplifiers will be a few microseconds.

DAC Structure Generally speaking, a DAC is used as a black box, and no knowledge of the internal workings is required. There is some value, however, in briefly showing how such conversion can be implemented. The simplest conversion uses a series of op amps for input for which the gains have been selected to provide an output as given by Equation (3.3). The most common variety, however, uses a *resistive ladder network* to provide the transfer function. This is shown in Figure 3.10 for the case of a 4-bit converter. With the *R-2R* choice of resistors, it can be shown through network analysis that the output voltage is given by Equations (3.3) or (3.4). The switches are analog electronic switches.

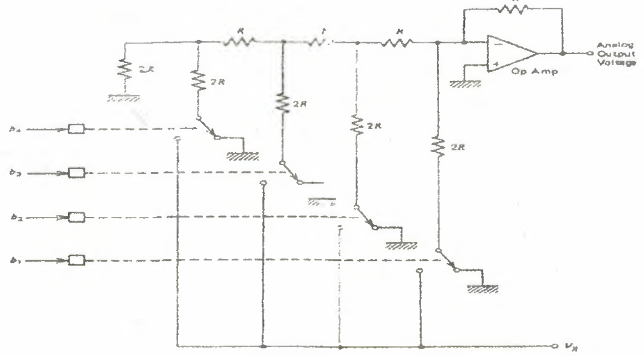


Figure 3.11 A typical DACs often implemented using a ladder network of resistors

R-2R ladder

The scaled resistor technique becomes awkward when you have more than a few bits. For example, in a 12-bit converter you would need a range of resistor values of 2000:1, with corresponding precision in the small resistor values. An elegant solution is provided by the R-2R ladder, shown in Figure 3.12. Only two resistor values are needed, from which the R-2R network generates binary-scaled currents. Of course, the resistors must be precisely matched, though the actual resistor values are not critical. The circuit shown generates an output of zero to -10 volts, with "full output" corresponding to an input count of 16 (again, the maximum input count is 15, with output voltage of 10*15/16). With a few modifications, an R-2R scheme can be used for BCD conversion.

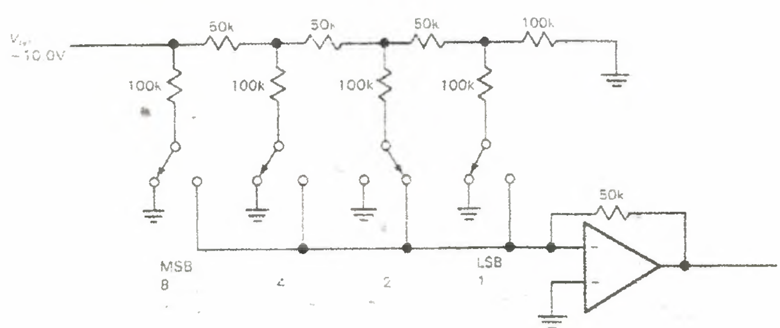


Figure 3.12 R-2R ladder

Scaled current sources

In the R-2R converter in the. Preceding paragraph, the op-amp converts binary scaled currents to an output voltage. Although an output voltage is often most convenient, the op-amp tends to be the slowest part of the converter circuit. In situations where you can use a converter with current output, you will get better performance, usually at lower price. Figure 3.13 shows the general idea. The currents can be generated by an array of transistor current sources with scaled emitter resistors, although IC designers usually use instead an R-2R ladder of emitter resistors. In most converters of this type, the current sources are ON all the time, and their output current is switched to the output terminal or to ground, under control of the digital input code. Watch out for limited output compliance in current-output DACs; it can be as little as 0.5 volt, though values of a few volts are typical.

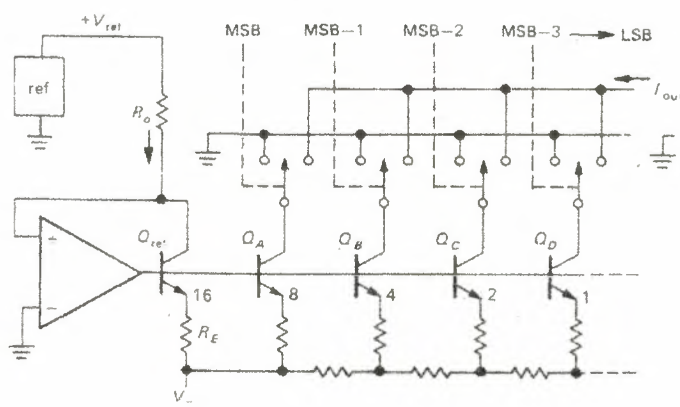


Figure 3.13 Classic current switched DAC.

Generating a voltage output

There are a few ways to generate an out-put voltage from a current DAC. Figure 3.14 shows some ideas. If the load capacitance is low, and large voltage swings aren't needed, a simple resistor to ground will do nicely. With the usual 1mA full-scale output current, a 100 ohm load resistor will give l00mV full-scale output with 100 ohms output impedance: If the capacitance of the DAC's output combined with the load capacitance doesn't exceed l00pF, you will get 100ns settling time in the preceding example, assuming the DAC is that fast. When worrying about the effect of RC time constants on DAC output response, don't forget that it takes quite a few RC time constants for the output to settle to within ½ LSB of the final voltage. It takes 7.6 RC time constants, for instance, to settle to within I part in 2048, which is what you would want for a 10-bit converter output.

To generate large swings, or to buffer into small load resistances or large load capacitances, an op-amp can be used in the transresistance configuration (current-to-voltage amplifier), as shown. The capacitor across the feedback resistor may be necessary for stability, because the DAC's output capacitance in combination with the feedback resistance introduces a lagging phase shift; unfortunately, that compromises the speed of the amplifier. It is an irony of this circuit that a relatively expensive high-speed (fast-settling) op-amp may be necessary to maintain the high speed of even an inexpensive DAC. In practice, the last circuit may give better performance, since no compensation capacitor is needed. Watch out for offset voltage error, since the op-amp's input offset voltage is amplified 100 times.

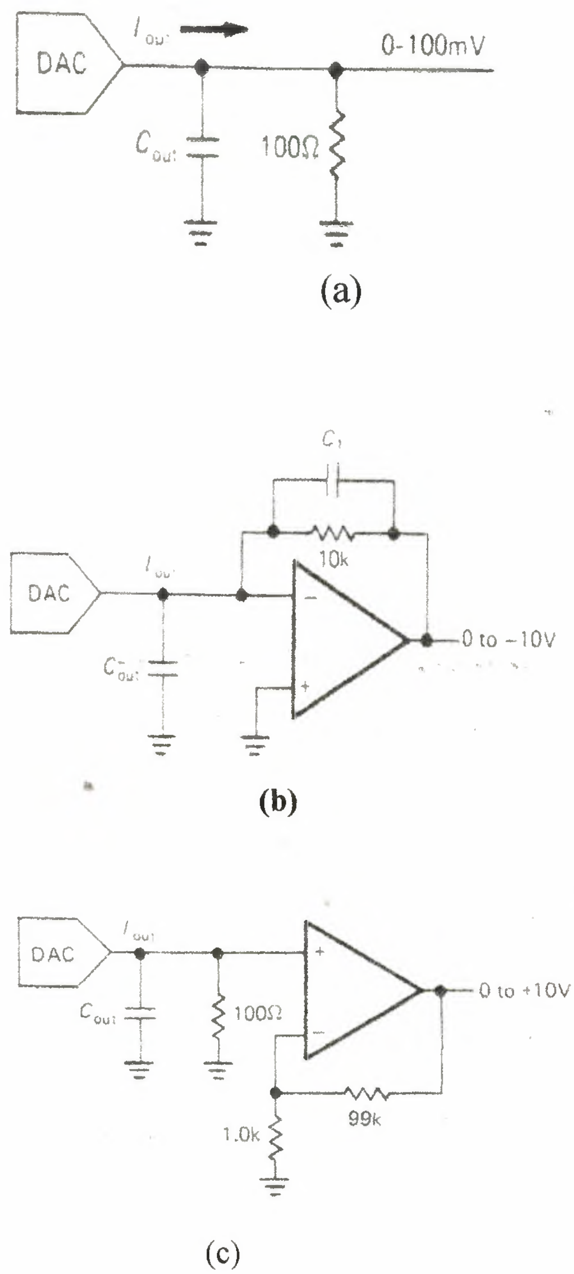


Figure 3.14 Generating voltages from current output DACs.

Data Output Boards

It is now common and convenient to obtain a printed circuit board that plugs into a personal computer expansion slot and is a complete data output system. The board has all necessary DACs. address decoding, and bus interface. In most cases, the supplier of the board will also provide elementary software, often written in C. BASIC, or assembly language, as necessary to use the board for data output.

3.4.4 Analog-to-Digital Converters (ADCs)

Although many sensors that provide a direct digital signal output exist and 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 the same manner as Equation (3.3) in that some analog voltage is provided as input, and the converter finds a binary number that, when substituted into Equation (3.3), gives the analog input. Thus,

$$V_{in} \simeq V_R[b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}] \qquad \textbf{(3.7)}$$

where V_{in} = analog voltage input

V_R = reference voltage

$b_1, b_2, \ldots b_n$ = n-bit digital outputs

We use an approximate equality in this equation because the voltage on the right can change by only a finite step size given by Equation (3.5).

$$\Delta V = V_R 2^{-n}$$

Therefore, there is an inherent uncertainty of ΔV in any conversion of analog voltage to digital signal. This uncertainty must be taken into account in design applications. If the problem under consideration specifies a certain resolution in analog voltage, then the word size and reference must be selected to provide this in the converted digital number. Equation (3.7) can be written in a simpler fashion, by expressing the fractional number as the fraction of counting states, as was done for the DAC. In this case the base-10 value of the digital output can be expressed as:

$$N = \mathrm{INT}\left(\frac{V_{in}}{V_R} 2^n\right) \quad \textbf{(3.8)}$$

where INT( ) means to take the integer part of the quantity in brackets. This is not a round-off, but rather a truncation, so that INT(3.3) = 3 and INT(3.99) = 3 also. The value of N is then converted to hex and/or binary to demonstrate the ADC output. In the previous example, we would have:

$$N = \mathrm{INT}\left(\frac{3.127}{5} 2^5\right) = \mathrm{INT}(20.0128) = 20_{10} \quad \textbf{(3.9)}$$

or 14H = $\mathbf{10100_2}$, as already found.

Bipolar Operation

A bipolar ADC is one that accepts bipolar input voltage for conversion into an appropriate digital output. The most common bipolar ADCs provide an output called offset binary. This simply means that the normal output is shifted by half the scale so that all zeros corresponds to the negative maximum input voltage instead of 0. In equation form, the relation would be written from Equation (3.7) as

$$N = \mathrm{INT}\left[\left(\frac{V_{in}}{V_R} + \frac{1}{2}\right) 2^n\right] \quad \textbf{(3.10)}$$

From this equation, you can see that if V_{in} = - $V_R/2$, then the output is zero, N = 0. If V_{in} = 0, then the output would be half of 2^n. The output will be the maximum count when the input is $V_R/2 - V_R2$^n. For example, for 8 bits with a 10.0-volt reference, the step size is ΔV_{in} = (10)2^8 = 0.039 volts. Looking at the possible states, we would have

$$\begin{array}{ll}
V_{in} = -5.000 & N = 00000000_2 \\
V_{in} = -4.961 & N = 00000001_2 \\
\quad \text{etc.} & \\
V_{in} = -0.039 & N = 01111111_2 \\
V_{in} = 0.000 & N = 10000000_2 \\
V_{in} = +0.039 & N = 10000001_2 \\
\quad \text{etc.} & \\
V_{in} = +4.961 & N = 11111111_2
\end{array}$$

There is an asymmetry to the result so that the converter cannot represent the full range from minus to plus $V_R/2$.

ADC Characteristics

Figure 3.15 shows a generic ADC with all the typical connections. It is quite possible and even appropriate in many cases to regard the ADC as simply a black box with certain input and output characteristics, The following list summarizes the important characteristics of the ADC.

1. ***Analog voltage intput*** This is for connection of the voltage to be converted. As will be explained later, it is important that this voltage be constant during the conversion process.
2. ***Power supplies*** Generally, an ADC requires bipolar supply voltages for internal op amps and a digital logic supply connection.
3. ***Reference voltage*** The reference voltage must be from a stable, well-regulated source. Special, integrated circuit reference-source voltages are available for this purpose.
4. ***Digital outputs*** The converter will have n output lines for connection to digital interface circuitry. Generally, the levels are typical TTL values for definition of the high and low states. It is common for the output lines to be tri-state outputs so that the ADC can be connected directly to a bus.

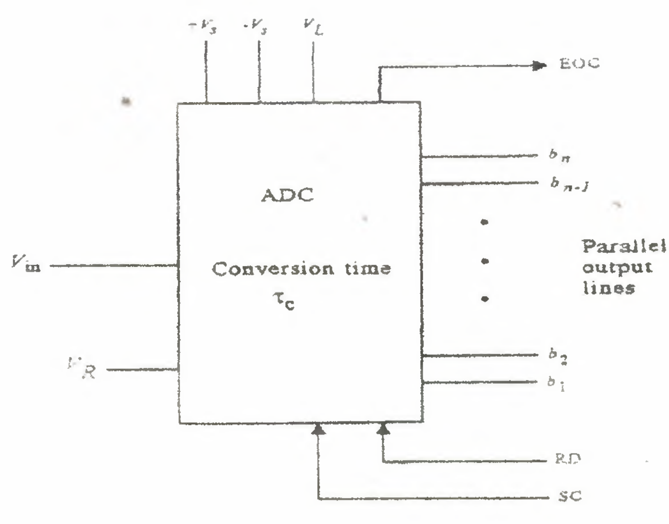


Figure 3.15 A generic ADC diagram, showing typical input and output signals and noting the conversion time.

5. *Control lines* The ADC has a number of control lines that are single-bit digital inputs and outputs designed to control operation of the ADC and allow for interface to a computer. The most common lines are:

a. SC (Start convert) This is a digital input to the ADC that starts the converter on the process of finding the correct digital outputs for the given analog voltage input. Typically, conversion starts on a falling edge.

b. EOC (End of convert) This is a digital output from the ADC to receiving equipment, such as a computer. Typically, this line will be high during the conversion process. When the conversion is complete the line will go low, Thus. the falling edge indicates that the conversion is complete.

c. RD (Read) Since the output is typically buffered with tri-states. even though the conversion is complete, the correct digital results do not appear on the output lines. The receiving equipment must take the RD line low to enable the tri-states and place the data on the output lines.

6. *Conversion time* This is not an input or an output, but a very important characteristic of ADCs. A typical ADC does not produce the digital output instantaneously when the analog voltage is applied to its input terminal. The ADC must sequence through a process to find the appropriate digital output, and this process takes time. This is one of the reasons that handshaking lines are required. Figure 3.16 shows a typical timing diagram for taking a sample of data via an ADC.

The existence of a finite conversion time complicates the use of ADCs in data acquisition. The computer cannot have a data input at any time: rather, it must request an input, wait for the ADC to perform a conversion, and then input the data.

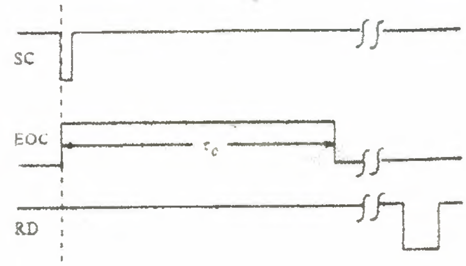


Figure 3.16 A typical data-acquisition timing diagram using an ADC. The read operation may occur at any time after the end-of-convert has been issued by the ADC.

ADC Structure Most ADCs are available in the form of integrated circuit (IC) assemblies that can be used as a black box in applications. To fully appreciate the characteristics of these devices, however, it is valuable to examine the standard techniques employed to perform the conversions. There are two methods in use that represent very different approaches to the conversion problem.

Parallel-Feedback ADC The parallel-feedback A/D converter employs a feedback system to perform the conversion, as shown in Figure 3.17, Essentially, a comparator is used to compare the input voltage V_x to a feedback voltage V_F that comes from a DAC as shown. The comparator output signal drives a logic network that steps the digital output (and hence DAC input) until the comparator indicates the two signals are the same within the resolution of the converter. The most popular parallel-feedback converter is the *successive approximation* device. The logic circuitry is such that it successively sets and tests each bit, starting with the most significant bit of the word. We start with all bits zero. Thus, the first operation will be to set $b_1 = 1$ and test $V_F = V_R 2^{-1}$ against V_x through the comparator.

If V_x *is* greater, then b1 will be 1; b_2 is set to 1 and a test is made of V_x versus $V_y = V_R(2^{-1} + 2^{-2})$, and so on.

If V_x is less than $V_R 2^{-1}$, then b_1 *is* reset to zero; b_2 is set to 1, and a test is made for V_x versus $V_R 2^{-2}$. This process is repeated to the least significant bit of the word.

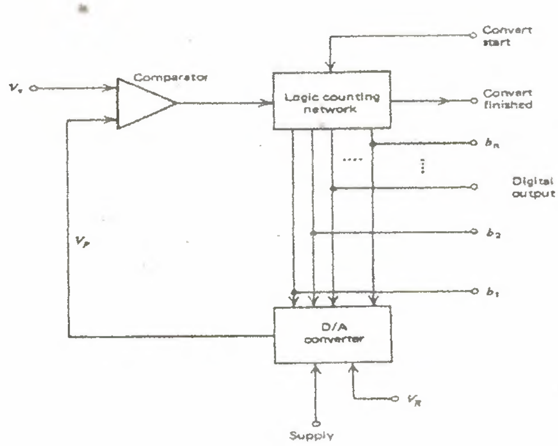


Figure 3.17 One common method of implementing an ADC is the successive approximation or parallel feed back system. This uses an internal DAC.

The conversion time of successive approximation-type ADCs is on the order of 1 to 5 μs per bit. Thus, a low-priced 8-bit ADC might require 5μs/bit for a total conversion time of about 40 μs. *A* higher-quality (and price) 12-bit might be able to perform the full conversion in only 15 μs.

These conversion times depend on a clock that is internal to the ADC and not crystal controlled. Thus, there will be variation of the conversion time from unit to unit.

Ramp ADC The ramp-type A/D converters essentially compare the input voltage against a linearly increasing ramp voltage. A binary counter is activated that counts ramp steps until the ramp voltage equals the input. The output of the counter is then the digital word representing conversion of the analog input. An op amp integrator circuit typically generates the ramp itself.

Dual Slope Ramp ADC This ADC is the most common type of ramp converter. A simplified diagram of this device is shown in Figure 3.18. The principle of operation is based on allowing the input signal to drive the integrator for a fixed time T_1, thus generating an output of

$$V_1 = \frac{1}{RC}\int V_x\,dt \tag{3.11}$$

or, because Vx *is* constant.

$$V_1 = \frac{1}{RC}T_1 V_x \tag{3.12}$$

After time T_1, the input of the integrator is electronically switched to the reference supply. The comparator then sees an input voltage that decreases from V_1 as

$$V_2 = V_1 - \frac{1}{RC}\int V_R\,dt \tag{3.13}$$

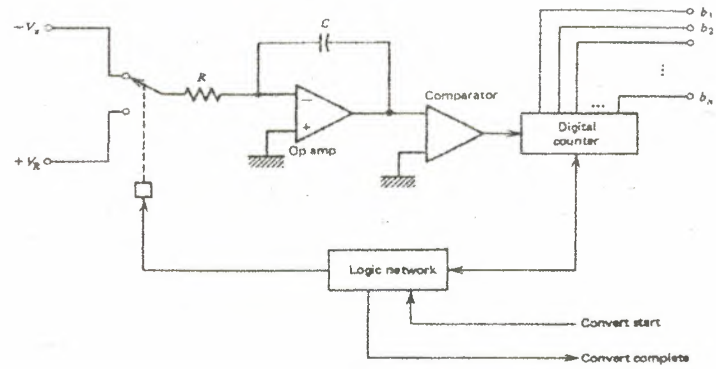


Figure 3.18 The dual-slope ADC uses an op amp integrator, comparator, and counter. This is commonly used in digital voltmeters.

or, because V_R is constant and V_1 *is* given From Equation (3.12),

$$V_2 = \frac{1}{RC} T_1 V_x - \frac{1}{RC} t V_R \qquad \textbf{(3.14)}$$

A counter is activated at time T_1 and counts until the comparator indicates $V_2 = 0$, at which time t_x [Equation (3.14)] indicates that V_x will be

$$V_x = \frac{t_x}{T_1} V_R \qquad \textbf{(3.15)}$$

Thus, the counter time t_x is linearly related to V_x and is independent of the integrator characteristics, that is, *R* and C. This procedure is shown in the timing diagram of Figure 3.19. Conversion *start* and *complete* digital signals are also used in these devices, and (in many cases) internal or external references may be used.

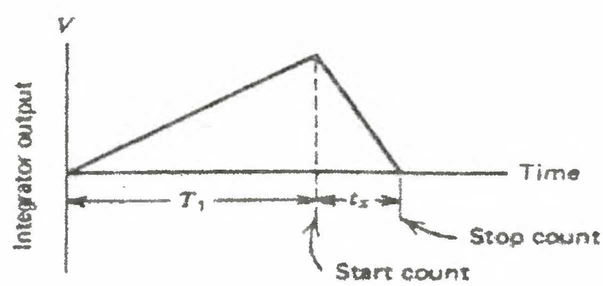


Figure 3.19 A typical timing diagram of a dual-slope ADC. Since both slopes depend upon R and C, the ADC output is independent of the values of R and C.

One of the most common applications of the dual-slope ADCs is in digital Multimeters. Here input circuitry converts the input voltage into an appropriate range for the ADC. The ADC performs conversions continuously: that is, when one conversion is finished the output is latched into a display register and another conversion is started. In applications such as this a few hundred milliseconds conversion time is plenty fast and allows for the display to be updated several times per second.

Parallel encoder

In this method the input signal voltage is fed simultaneously to one input of each of n comparators, the other inputs of which are connected to n equally spaced reference voltages. A priority encoder generates a digital output corresponding to the highest comparator activated by the input voltage Figure 3.20.

Parallel encoding (also called "flash" encoding) is the fastest method of A/D conversion. The delay time from input to output equals the sum of comparator plus encoder delays. Commercial parallel encoders are available with 16 to 1024 levels (4-bit to 10-bit outputs). A typical flash ADC is the TRW TDC1048, a bipolar 8-bit 20MSPS converter in a 28pin package.

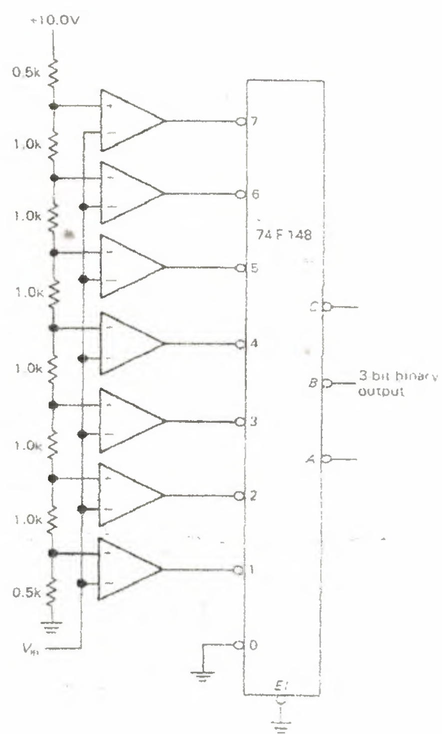


Figure 3.20 Parallel-encoded ("flash") A/D converter (ADC).

A variant on the simple parallel encoder is the so-called half-flash technique, a two step process in which the input is flash-converted to half the final precision; an internal DAC converts this approximation back to analog, where the difference "error" between it and the input is flash-converted to obtain the least significant bits (Fig. 9.50). This technique yields low-cost converters that are faster than any thing else except full flash converters. It is used in inexpensive converters like the 8-bit ADC0820 (national) and AD7820/4/8 (Analog Devices).

Flash encoders are worth considering in waveform digitizing applications even when the conversion rate is relatively slow, because their high speed ensures that the input signal is effectively not changing during the conversion. The alternative - the slower converters we'll describe-next - usually requires an analog sample-and-hold circuit to freeze the input waveform while conversion is going on.

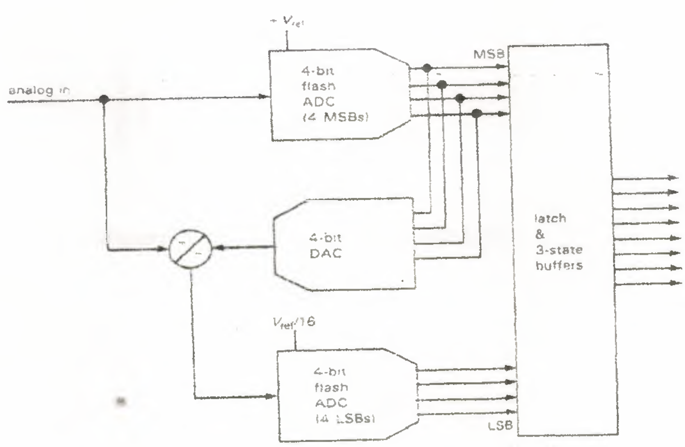


Figure 3.21 Half-flash ADC

3.5 MODULATION

A problem that is often encountered with dealing with the transmission of low level d.c. signals from sensors is that the gain of an operational amplifier used to amplify them may drift and so the output drifts. This problem can be overcome if the signal is alternating rather than direct. In addition, the conversion of the signal to alternating can assist in the elimination of external interference from the signal.

One way this conversion can be achieved is by chopping the d.c. signal in the way suggested in figure 3.22. The output from the chopper is a chain of pulses, the heights of which are related to the d.c. level of the input signal. This process is called *pulse amplitude modulation.* After amplification and any other signal conditioning, the modulated signal can be demodulated to give a d.c. output. With pulse amplitude modulation, the height of the pulses is related to the size of the d.c. voltage. An alternative to this is *pulse width modulation* where the width, i.e. duration, of a pulse depends on the size of the voltage (figure 3.23).

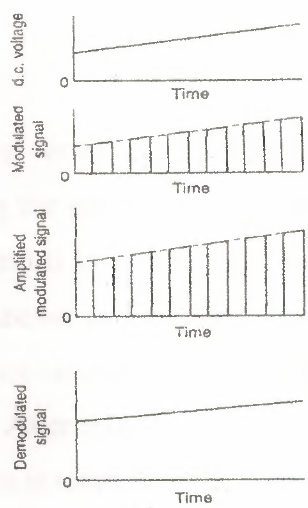


Figure 3.22 pulse amplitude modulation

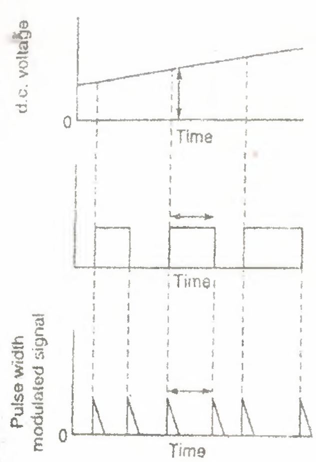


Figure 3.23 pulse duration modulation

The above refers to d.c. signals, however it is often necessary to modulate a.c. signals. This enables data transmission at much higher frequencies and so allows the use of high-pass filters to eliminate the noise signals that usually occur at much lower frequencies. Modulation techniques used are amplitude modulation figure 3.24(a), phase modulation and frequency modulation figure 3.24(b). With amplitude modulation the amplitude of a carrier wave, of much higher frequency than the input, is varied according to the size of the voltage input, i.e. the wave carrying the signal from the sensor. Thus for a carrier wave that can be represented by

$$V = V\sin(\omega t + \phi)$$

The amplitude term V is varied according to the way the voltage input varies. Phase modulation involves varying the phase ϕ of the carrier wave according to the size of the voltage input. Another method is to vary the angular frequency ω according to the size of the voltage input. This is known as frequency modulation. Both phase modulation and frequency modulation produce similar effects, a modulated wave with a frequency, which relates to the input voltage. After transmission, the signal can be demodulated so that an output can be obtained which is related to the original signal before it was modulated.

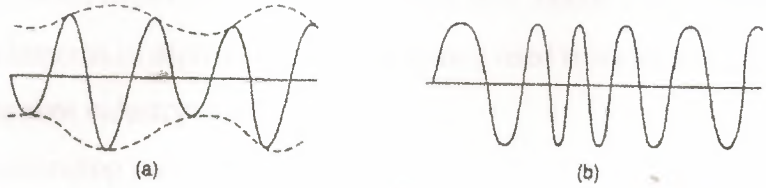


Figure 3.24 Modulation: a) Amplitude, b) Frequency.

CONCLUSION

The objective of the signal conditioning elements in Mechatronics is the search for new engineering solutions for industrial applications inspired by principles, functions, mechanisms and architectures found in living organisms. Currently the focus is on the signal conditioning systems featuring an efficient implementation of control system and information processing tasks in Analog, digital, and mixed circuitry.

The application scope for signal conditioning elements that include information processing for making decisions or eliciting actions on a local and autonomous basis is quite large. It extends to surveillance, industrial control, robotics, environmental control, the automotive sector, consumer electronics and multimedia applications. Typical requirements for sensor systems in these domains are reliability, real-time processing, high accuracy, compactness, low power consumption, and finally low-cost.

Many of the results that have been obtained in research are introduced into new industrial developments, such as, for example, analog or digital conditioning elements that we use it after the torque sensors for electrical power steering in cars. And much other application.

These are the some of the important features of signal conditioning elements:

- Includes a detailed treatment of linear and nonlinear analog signal processing.
- Introduces elements of digital signal conditioning used in measurement.
- Discusses current industry trends.
- Contains challenging problems.
- By using signal conditioning elements we can get complete isolation.
- Banishment all types of environment noise by using the compensation elements.
- For the op-amp portion of design, the easiest design approach is to develop an equation for the output versus input.
- In this type of elements we can get full linearized for the signal, which we take it from the output of the sensors.
- Banishment all the noise and take some levels of the signal by using the filtering.

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