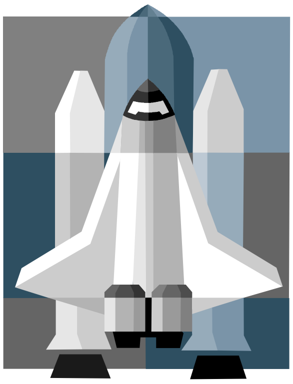
CHAPTER (1)



Introduction to control systems

Objectives:

This chapter will consider the overall process-control loop, its function, and its description. After you have read this chapter, you should be able to

- Identify the control loop elements
- Describe the function of each control element
- Compare between open loop and closed loop
- Investigate the role of feedback and feed-forward
- Compare between process control and servo control
- Define technical words in the control loop

1.1 Introduction

Automatic control systems are widespread in nature, home, and industry. Many applications can be encountered in our daily life such as TV, Cassette, air conditioner, refrigerator, washing machine, mobile phone, cars, computers … etc. For example, your body temperature remains almost constant ($\approx 37^o$) regardless of whether you are in a cold or hot environment. To maintain this constancy your body has a temperature control system. If your temperature begins to increase above the normal you sweat, if it decreases you shiver. Both these are mechanisms which are used to restore the body temperature to its normal value. Another example, if you go to pick up a pencil from a bench there is a need for you to use a control system to ensure that your hand actually ends up at the pencil. This is done by observing the position of your hand relative to the pencil and making adjustments in its position as it moves towards the pencil. This control system is controlling the positioning and movement of your hand.

Developments in various fields of engineering have resulted in very sophisticated machines, devices and manufacturing processes. Successful operation of these devices and process requires: very short response time, large amount of complexity, repetitious analytical and mechanical operations, and low tolerance to errors that are well beyond human abilities. Automation became the only alternative for continuing the technical progress. While design of a particular automatic control, it was found that all control systems operate according to the same principle known as the *negative feedback*. Negative feedback mechanisms can be easily detected in many biological, economical and physical systems capable of maintaining equilibrium.

Analog controllers based on electronic cards, electronic timers, electronic counters, and control relays were used widely in the early control applications. In the beginning of 1970s, the digital microprocessor is created and changed completely the control design concepts. Thereafter, digital controllers have taken the increasing attention to replace old analog controllers by advanced digital controllers such as micro-controllers, programmable logic controllers, and computers. The sophisticated hardware functions are replaced by software programs to carry out a high reliable design approach within low cost.

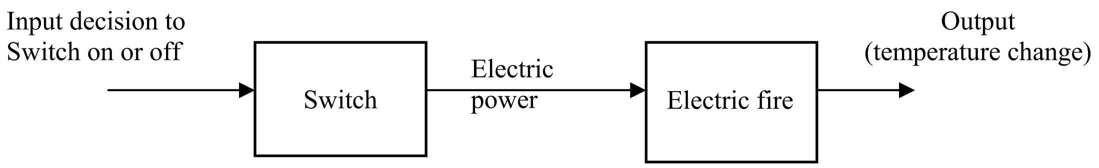
Computers became the beginning of the new era in control engineering. *First*, computers allowed for full-scale implementation of powerful mathematical tools provided by numerical analysis and matrix theory in analysis and design. *Second*, computers allowed for numerical simulation of control and dynamic systems, providing the most accurate and thorough analytical and design tools. *Third*, a computer became a part of a control system, implementing in software the most sophisticated algorithms for monitoring, data logging, and control. Modern age controls became one of the most mathematical and computer-saturated fields of engineering. Interdisciplinary by nature, control engineering offers its services and general methods to electrical, mechanical, aerospace and power engineering, as well as metallurgy, biology, material science,…etc. Control theory provides a foundation for such new disciplines as intelligent (smart) machines, bioengineering, and robotics. Computer-based control engineering allows for the development of new technologies utilizing physical phenomena that are inherently unstable.

In fact, instrumentation and process control is found in almost every device or process you will ever encounter, on or off the job. An example of a task demonstrating simple process control and instrumentation concepts would be someone filling a container with water from a faucet (simple valve) to some preset level. The *instrumentation* part of this task would be the container with markings on its side indicating volume. The *process control* part of the task would be the control of water flow from the faucet. As the level of the water reaches some predetermined point on the container, commonly called the *set point*, the flow of the water is gradually decreased and ultimately stopped. Another example would be someone maintaining a certain speed on a speedometer in an automobile. The instrumentation part of this process would be the speedometer. The process control part of this task would be the operation of the accelerator pedal, which controls the flow of gasoline to the engine. The driver pushes down or lets off the accelerator pedal to maintain the speedometer setting at a predetermined speed.

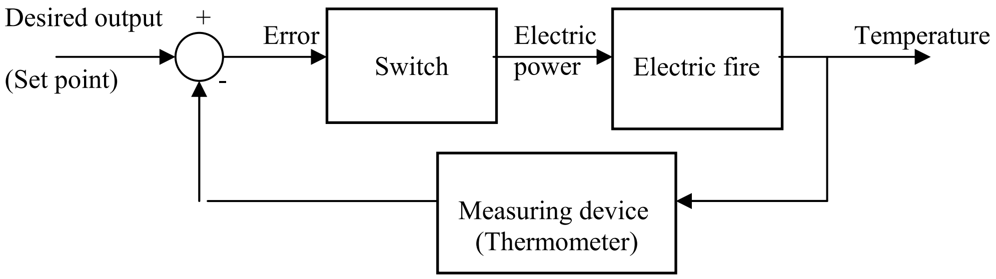
In both of these examples, a person acts as a controller in the process. The person visually gathers information about the flow rate of water or the speed of the automobile and performs a controlling action. This controlling action will be either turning the faucet handle or pressing the accelerator pedal to make changes in the process to bring it in line with the desired result, which is so-called ***manual control***. While there are process control systems which have to be adjusted by a person reading a gauge or readout, much instrumentation and process control systems used in industrial setting are automated. In many areas of industry, the trend is towards fully automated systems using digital controllers monitored and operated by computers. Process instrumentation and control plays a critical part in assuring that flow rates, temperatures, pressures, liquid levels, and any physical variables are in the desired ranges. This assures that the processes we are working with are operating at safe, cost-effective, and accurate performance (***automatic control***).

1.2 Open-loop and closed-loop systems

There are two basic forms of control systems, one being called open-loop and the other closed-loop. The difference between these can be illustrated in the following example.



(a) Open-loop system



(b) Closed loop system

Figure 1.1 Heating room system

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/she might just switch on the element of 1 KW, if they want the room to be at not too high a temperature. The room will heat up and reach a temperature corresponding to this element. If there are changes in the conditions, perhaps someone opening a window, there is no way the heat output can be adjusted to compensate. This is an example of open-loop control in that there is no information fed back to the element to adjust it and to maintain a 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 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 the two values is determined by a comparison- the person in this case. A simple block diagram representation is given in figure 1.1 to illustrate the two cases.

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 the required values. They are, whoever, more complex and so more costly with a greater chance of breakdown as a consequence of the greater number of components.

1.3 Process variables and process instrumentation

The parts of the process that we are trying to control are referred to as the *process variables*. Any condition that causes a process variable to deviate from the desired level or "set point" is referred to as a *process upset*. Depending on the process we are working with, there are many different kinds of process variables that we may want to control. Some typical examples of process variables are liquid level, fluid flow rate, temperature, pressure, voltage rate or resistance (when working with electricity), density or PH (when working with a chemical process), and position or speed (when working with mechanical systems).

The devices that are used to monitor and control these variables are generally referred to as *process instrumentation* or simply instrumentation. Instruments have two basic jobs, and may combine both tasks into one device. *First*, they measure and indicate the value of a process variable, which may then show up as information on a readout, gauge, recorder…etc. *Secondly*, after comparing the variable reading to some predetermined value (or set point), they send out a controlling signal to another element in the system. Typically this might be a valve or heating element, which causes a change in the operation. Such a change might be a valve opening or closing, or a heating element increasing or decreasing the temperature. This has the effect of changing the process enough to bring the process variable in line with the set point.

1.4 Basic elements in closed loop control

In a simple situation, it may be possible for one operator to manually deal with all the process variables and control them, but a process becomes more complex, the number of process variables and upsets that must be dealt with increases. Additionally, as in the case of an offshore platform or gas processing facility, these processes are physically spread out over a large area. In such cases, *automatic process control* systems are installed. An automatic process control system does exactly what the name implies; it automatically controls a process and its variables. Depending on the location where they are installed, automatic process controls will vary in their shape, size, and components. However, regardless of location, all automatic process control systems contain the following main elements:

1) A primary measuring element (sensor)
2) A transmitting element (transducer)
3) A controller, and
4) A final control element

The level control system in figure 1.2 controls the flow of water into and out of a holding tank or reservoir. The desired level of the tank is referred to as the set point. The demand on the tank causes the water level to drop and consequently causes a float in the tank to drop as well.

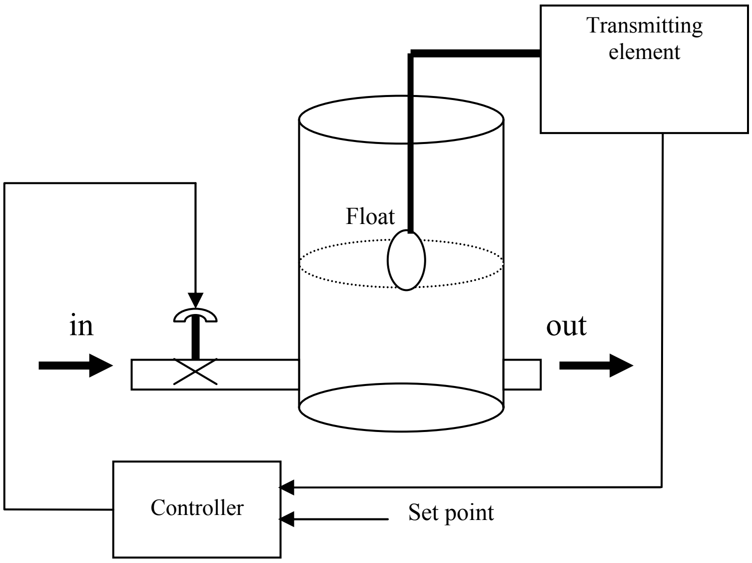


Figure 1.2 Level control

This float is the *primary measuring element* of our simple system. The primary element is the part of the system that detects a process upset or change in the value of a process variable. The primary element is linked to the *transmitting element*. The transmitting element converts the motion of the primary measuring element into a signal (typically a change in pressure in a pneumatic line or an electric signal) which represents the value of the process upset. This signal or value is then sent to (or input) to the *controller* where it is compared to a value representing the desired set point. The difference between the two values (set point and upset) is then computed, and another signal is sent out (output) to the *final control element*, in this case, a valve. This output signal is proportional to the amount of corrective action necessary by the valve to bring the process variable (water level) back to set point

1.5 Feedback control

In our example, if the level increases above the set point, the automatic process control system will control the valve until it is partially closed or, if necessary, shut completely. If the level drops blow the set point, the valve is opened, allowing more water to enter the reservoir. As the level of the water changes, this information is sensed by the level sensing primary element. This new level becomes information that is fed back into the control system. This process of:

- Sensing the level of the water
- Comparing it against a desired value
- Making a change in the process to bring the process variable in line with the set point and then
- Feed back the new information to the level controller is commonly referred to as feedback control.

Because of the cyclical or "looping" nature of feedback control, a process that uses feedback control is sometimes referred to as a "*feedback loop*". Therefore, it can compensate unmeasured disturbances in the loop. Feedback control may be either manual or automatic. The difference between automatic and manual control systems is that automatic control systems use instruments and automatic control equipment to control the process, whereas manual systems use an operator to make decisions and adjustments. The system we have shown is automatic, with little need for anyone to interact with the process once it is placed into service. It may be desirable, however, to add additional instrumentation to give an operator updated information about the status of the system. For example, a chart or a strip recorder can be added to record process upsets over a period of time, or a warning signal can be added, activated by a very high or low level in the tank. Another example of a feedback control system is a gas-fired water heater as shown in figure 1.3. The desired temperature of the water in the tank is controlled by the use of a feedback mechanism which controls the fuel gas supply to the gas-fired heater. If the temperature of the output water is too hot, the amount of fuel gas going to the heater is reduced. If the output water is too cool, the supply of fuel gas is increased.

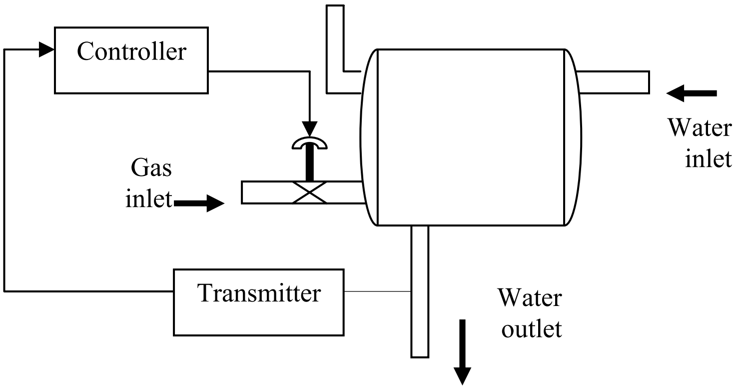


Figure 1.3 Feedback control of Gas-fired water heater

The feedback is said to be *negative feedback* when the error signal is the difference between the desired value and the measured output value from the process. *Positive feedback* occurs when the reference value is added to the measured value. A simple example of positive feedback is the characteristic of an electric resistor. The higher its temperature is the lower its resistance. When a current passes through the resistor it becomes warm. A consequence of this is that the resistance decreases. This results in the current increasing. The increased current causes the resistor to become even warmer. A consequence of this is that its resistance decreases further. This results in an increase in current and so on. It is a positive feedback since the input, the current, is increased by the feedback from the output rather than maintained at a constant value (*unstable system*). Note that, negative feedback is able to stabilize the controlled system and maintains the output at a constant value (*stable system*).

1.6 Feed-forward control

Feedback systems and feedback control loops are the most common type of control found. However, there are the disadvantages in using just feedback control systems in all applications. In the example we have just seen, a simple feedback mechanism, the heater controlling the temperature of the water is not operated until after the temperature sensor detects a deviation from some set point. In many situations, this is unacceptable because it is critical to maintain certain process variables within a very small range. Suppose that in the example of heating water, the temperature range of the water in the vessel is critical. In instances such as this, it may be necessary to use *feed-forward* control. It is an open-loop strategy to predict and compensate as quick as the known (measured) disturbances. An automatic feed-forward control system installed on our water heater example as shown in figure 1.4.

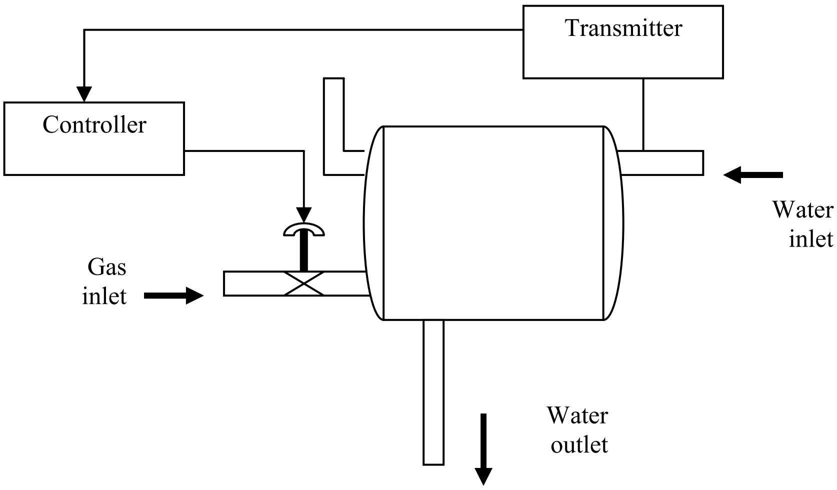


Figure 1.4 Feed-forward control of gas-fired water heater

In this example, a temperature sensing element is installed on the water inlet (as opposed to the feedback system where it is installed on the outlet). If the temperature of the incoming water changes a signal is sent to the measuring element, which is also a transmitter. The transmitter sends the signal to the controlling element, where it is then compared to the set point. If a difference is noted, the controlling element sends a proportional control signal to the final controlling element (the gas supply valve of the gas-fired heater), which then increases or decreases the temperature of the fire tube. The result of this feed-forward control is that the temperature of the controlled variable (in this case, the temperature of the heated water in the vessel) will be consistent. It is possible also to have a manual feed-forward control system. Here an operator would read a temperature gauge on the water inlet, mentally compare the figure to the set point, and adjust the gas-fired heater accordingly. The use of feed-forward control by itself is rare. In any process that might be found in industry, there are many possible disturbances that could arise. If, for example, the water output temperature were to change, a feed-forward control system by itself would not have the capability to sense this situation.

1.7 Combination feedback/feed-forward control

It can be concluded, therefore, that feedback normally presents the most practical technique for the development of a control system. However, in a situation when the controlled plant is affected by a small number of dominant disturbances, which can be properly monitored (measured); the feedback could be supplemented by a feed-forward mechanism, responsible for dominant disturbances. Because of the shortcomings of both the feedback and feed-forward control systems, what we usually find is the two control systems combined together as shown in figure 1.5. The feed-forward control loop compensates for changes in the inlet water temperature while the feedback control loop makes adjustments to compensate for other process disturbances. This combination of control loops allows for process control which will compensate for both inlet water temperature changes as well as for changes in the output water temperature.

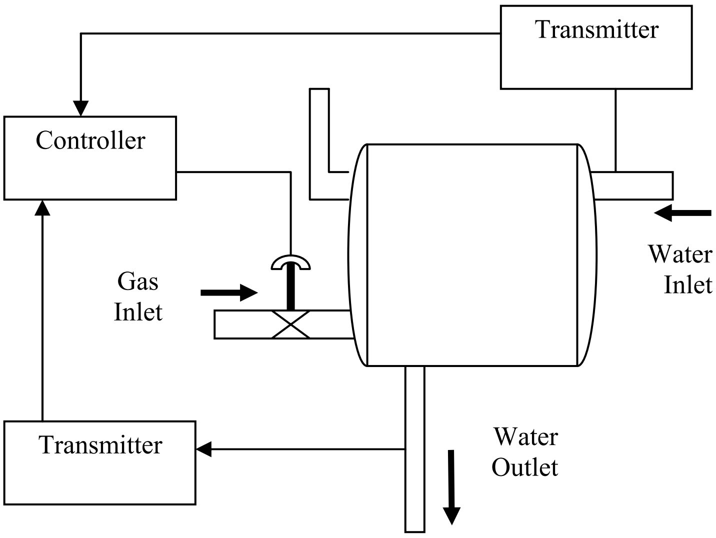


Figure 1.5 Feedback and feed-forward control

In general, automatic control has two major objectives:

- Firstly, closed loop system stability has to be guaranteed by the means of control system.
- Secondly, the best possible performance during transient and steady state response has to be provided by the controller

Control systems can be considered to fall in two main categories:

- *Process control system* where variables such temperature, liquid level, fluid flow, and pressure are maintained constant. Thus in a chemical process there may be a need to maintain the level of a liquid in a tank to a particular level or to a particular temperature. These variables are also commonly found in oil and gas industry. In this type of applications, the desired output for the controlled system is rare to be changed and it is required to maintain the output at this value (*regulation objective*) as shown in Fig. 1.6.

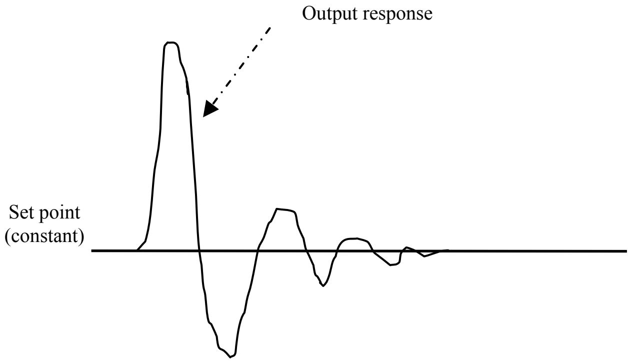


Figure 1.6 Regulation objective

- *Servo control system* involves consistently and accurately positioning some moving part or maintaining a constant speed. This might be, for example, a motor designed to run at a constant speed or a machining operation in which the position, speed and operation of a tool is automatically controlled. In this type of applications, the desired output for the controlled system could be frequently changed. Therefore, it is required to follow this change and to maintain the new desired value (*regulation plus tracking objectives*) as shown in Fig. 1.7.

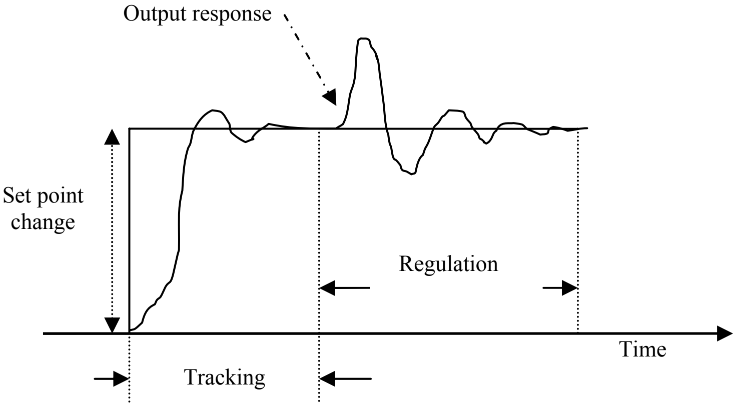


Figure 1.7 Tracking and regulation objectives

1.8 Signals in control loop

Two analog standards are in common use as a means of representing the range of variables in control systems as shown in Fig. 1.8. For electrical systems we use a range of electric current carried in wires, and for pneumatic systems we use a range of gas pressure carried in pipes. These signals are used primarily to transmit variable information over some distance, such as to and from the control room and the process in the field.

- *Current* is used to transmit measurement data about the controlled variable to the control room then it can be converted into voltage signal. The most common current transmission signal is 4 to 20 mA. Thus, if we measure a temperature that ranges from 20 ^{o}C to 150 ^{o}C, 4 mA might be represents 20 ^{o}C and 20 mA represents150 ^{o}C, with all temperatures in between represented by a proportional current. Current is used instead of voltage because the system is then less dependent on load (loading effect problem).

- *Pneumatic* signal can be used to actuate a valve that requires a voltage to pneumatic converter in the control room. The most common standard for pneumatic signal transmission is 3 to 15 psi. In this case, the voltage signal has to be converted into a proportional pressure of gas in a pipe. The gas is usually dry air to be safe in oil and gas industrial applications. The pipe may be many hundreds of meters long, but as long as there in no leak in the system the pressure will be propagated down the pipe.

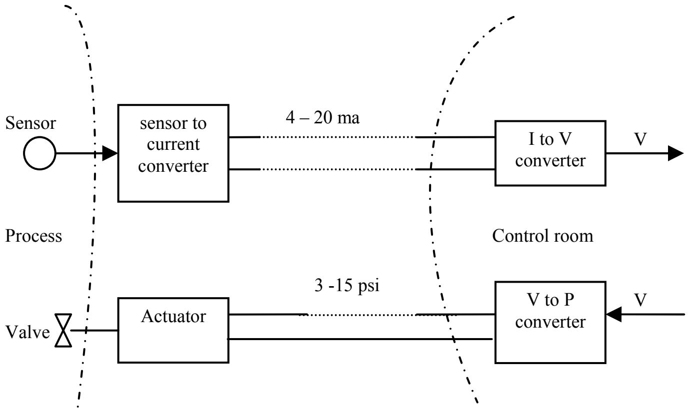


Figure 1.8 Signals from and to control room

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 systems 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 variable value and the value itself. For example, analog multi-meter has a pointer that moves to a position on its scale. The position value is proportional to the measured value.

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. For example, a digital multi-meter has a display number that represents the measured value. The device uses a limited number of discrete values for measurement display because a finite number of binary digits are used to represent data digitally. For example, suppose a variable voltage is to be represented digitally by a four digit binary number. That means, we have 16 different discrete values. If each discrete value represents in volt its decimal equivalent number, that means, $\mathbf{0101}_2$ in binary is equivalent to 5 volts measurement. The representation cannot distinguish between 5.25 and 5.57 volts because both are represented by binary number $\mathbf{0101}_2$. See Appendix A for the conversion between number systems.

1.9 International system of units

The metric system of units has been adopted by most technical disciplines. In process control, a particular set of metric units is used SI, called international system of units (CGS). The international system of units is maintained by an international agreement for worldwide standardization. The system is based on seven well-defined base units and two supplementary, dimensionless units. Everything else falls into category of defined units, meaning defined in terms of the seven base and two supplementary units as shown in the following table.

Table 1.1 International System of Units (CGS)

Quantity	Unit	Symbol
Base:		
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd
Supplementary:		
Plane angle	Radian	rad
Solid angle	Steradian	sr

All other SI units can be derived from these nine units, although in some cases a special name is assigned to derive the quantity. Thus, a force is measured by the Newton (N), where 1 N = 1 kg m/s^2; energy is measured by the joule (J) or watt-sec (W-s), given by 1 J = 1 kg m^2/s^2; and so on. Technical work in the United States is still done in the English system of units, it is necessary to perform transformations between these systems. However, SI units are often used in this book.

Example

Express a pressure of $p = 2.1 \times 10^3$ dyne/cm^2 in pascals. 1 Pa = 1 N/m^2.

Solution

WE know that, 1 m = 10^2 cm and 1 Newton = 10^5 dyne. Thus,

$$P=(2.1 \times 10^3 \text{ dyne/cm}^2)(10^2 \text{ cm/m})^2(1 \text{ N}/ 10^5 \text{ dyne}) = 210 \text{ pascals}$$

1.10 Generic control system

The following general definitions can be utilized in a generic control system:

- *To control* means to maintain a particular operation, status or performance of a physical process
- *Controlled plant or controlled process* is the physical process, i.e. the combination of physical transformations which must be maintained according to a precisely defined operational regime.
- *Controlled variable* represents quantitatively the actual operation, status or performance of the controlled process.
- *Control system* is a combination of components performing control functions. A control system typically forms a closed-loop with the controlled process.
- *Actuation signal* symbolizes the control efforts applied to the controlled plant in order to provide the desired effects on its status or performance.
- *Sensor* is the primary element that affected by the controlled (measured) variable change, usually might be a change in resistance or inductance or capacitance element or a small mechanical movement.
- *Transducer (transmitter)* is a device that transforms a controlled variable into an electrical signal thus providing the quantitative characterization of the actual operation, status or performance of the controlled process.
- *Set point (reference)* is the signal that represents the desired operation, status or performance of a controlled process. The controlled variables (referred to above) are represented by particular low power electric signals following some scale. The reference signals have the same order of magnitude and power as the signals representing controlled variables, but are defined by the human operators of the process.
- *Disturbance signals* represent all external (and sometimes internal) factors that result in the undesirable deviations of controlled variables from their required values. (e.g. thermal process with opened door)
- *Noise signal* is unwanted random signal in the measuring device or in the process.
- *Error detector* is the element to generate the error signal.
- *Error signal* is the difference between the actual and desired values of controlled variable, or between the reference and transducer output signals.
- *Controller* is an analog or digital device that defines the control efforts transforming the error signal into the control signal, in accordance with the control strategy.
- *Servomechanism* is an electric, hydraulic or pneumatic device that performs power amplification of the control signal, generating a control effort.
- *Actuator (final control element)* is the device, driven by the servomechanism, which directly affects the controlled process by applying the actuation signal.
- *Stable control system* is the system that maintains the controlled variable at its desired value.

Example

Apply the above definitions for a person controlling the temperature of a room using electric fire.

Answer

Controlled variable is the room temperature.
Set point (reference) is the required room temperature.
Comparison element is the person comparing the measured value with the required value of the temperature.
Error signal is the difference between required room temperature and its measured value.
Controller is the person.
Actuator is the switch on the fire.
Controlled process is the electric fire.
Sensor is a thermometer.

Example

Apply the above definitions for a person controlling the level of liquid inside a tank:

Answer

Controlled variable is the level.
Set point (reference) is the required level.
Comparison element is the person observing level marks through a glass on the tank side.
Error signal is the difference between required level and the observed value.
Controller is the working person.
Actuator is the valve.
Controlled process is the level of water in the tank.
Sensor is level marks device.

Example

Identify the basic control loop elements to control the speed of a DC motor.

Answer

Controlled variable is shaft speed.
Set point (reference) is the required speed in a voltage scale (you can use a potentiometer).
Comparison element is the difference amplifier.
Error signal is the difference between required speed and the measured value.
Controller is the amplifier (gain).
Actuator is the motor.
Controlled process is rotating shaft.
Transducer is tacho-generator output in volts.

1.11 Basic concepts (MCQ)

Place the letter of statement that **best** completes the sentence in space provided.

1] The parts of the process we are trying to control are referred to as _________.

A) Process control
B) Process variables
C) Process deviation

2] A Process upset is the result of the process deviating from the ___________.

A) Set point
B) Control element
C) Primary element

3] One of common process control variables is __________.

A) Displacement
B) Pressure
C) Acceleration

4] Automatic control systems contain the following elements: Primary measuring element, transmitting element, controller and ____________.

A) Reverse signal element
B) Final control element
C) Warning element

5] In feedback control systems, the primary measuring element is usually _________ of the final control element.

A) Upstream
B) Back
C) Downstream

6] Devices that control the value of process variables are known as ___________.

A) Final control elements
B) Feedback control
C) Transmitter

7] The primary measuring element for feedback control is located at the _________ of the controlled process.

A) controller
B) Inlet
C) Outlet

8] The primary measuring element for feed-forward control is located at the _________ of the controlled process.

A) controller
B) Inlet
C) Outlet

9] Pressure, flow, level, and flow are referred to as process ____________.

A) Upsets
B) Variables
C) Instruments

10] _______ is a desired pre-determined threshold.

A) Set point
B) Warning indicator
C) Feedback loop

11] Pneumatic control systems generally use the control signal in a range of __________.

A) 4-20 psi
B) 5-10 psi
C) 3-15psi

12] Electronic control systems generally use the control signal in a range of __________.

A) 5-10 mA
B) 0-20 mA
C) 4-20 mA

13] Sensor is the ________ that affected by the controlled variable.

A) Controller
B) Error detector
C) Primary element

14] ________ signals represent unwanted random signal in the measuring device or in the process.

A) Disturbance
B) Noise
C) Error

15] Regulation control objective has a ______ set point in the control loop.

A) Variable
B) Small
C) Constant

1.12 Problems

1] Explain the difference between open-loop and closed loop control.

2] Identify the basic elements in control systems involved in a
  a) driver steering a car
  b) refrigerator
  c) washing machine
Which of them is an open loop control system?

3] Is the driving of an automobile best described as a servomechanism or a process control system? why?

4] Explain the difference between positive and negative feedback and give an example of each. Which of them provides a stable control system?

5] The automatic control system for the temperature of a bath of liquid consists of a reference voltage fed into a differential amplifier. This is connected to a relay which then switches on or off the electrical heater to heat the liquid. Negative feedback is provided by a measurement system which feeds a differential voltage amplifier. Sketch a layout of the system and explain how the error signal is produced.

5] Water level in a reservoir of a chemical plant can increase due to rains, and decrease due to consumption and evaporation. It is controlled by pumping water from the lake or to the lake using a reversible pump. Suggest a control procedure for maintaining the required water level
a) using the feedback principle
b) using the feed-forward principle
Provide schematics and explain advantages and drawbacks of both systems.

6] Compare between process control and servo control systems. Give an example for each.

7] Atmospheric pressure is about 14.7 Ib/in^2 (psi). What is the pressure in pascals?

8] A controller output is a 4-20 mA current signal I that drives a valve to control flow Q. The relation between current and flow is $Q = 45\ (I\text{-}2\ \text{mA})^{1/2}$ gal/min. What is the flow for 12 mA? What current produces a flow of 162 gal/min?

10] Suppose the temperature range 20°C to 120°C is linearly represented by standard current range from 4 mA to 20 mA. What current will result from 66°C? What temperature does 6.5 mA represent?