PROCESS CONTROL
PRINCIPLES AND APPLICATIONS

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Introduction to Process Control

1.1 INTRODUCTION

Right from the early man, there has been a constant urge in human beings to explore the nature and control the environment to meet their needs. In fact, it is this strong and irresistible desire to mould the nature to suit their requirements that has distinguished men from other creatures.

Engineering science infact is concerned with understanding and controlling materials and forces of nature for the benefit of mankind. It is the science of applying the theoretical knowledge in practical life, to develop new products and systems that can cater to the needs of everyday life. Engineering is creativity; but it is heavily constrained by cost effectiveness of the product, concerns of safety, environmental impact, ergonomics, reliability, manufacturability, maintainability, and forces of nature. Control engineering is the engineering discipline that focuses on the mathematical modelling of systems of a diverse nature, analyzing their dynamic behaviour, and using control theory to make a controller that will cause the systems to behave in a desired manner.

The use of the word "control" is very common in everyday life, for example, anger control, diet control, pollution control, traffic control, etc. To an engineer, the word "control" means something more precise. From an engineer's point of view, control means an exact control in which output of a machine, process, or system instantly follows the demand setting of the input without any deviation. In actual practice, systems are so controlled that the deviation of actual output from the demanded input remains within an acceptable band after a reasonably short period of time. Numerical values of acceptable band and the time after which the variation comes to an acceptable range vary according to process requirements. Some processes can tolerate a good amount of deviation, some cannot. Output should change fast in some processes, while in others, slow change is acceptable.

Control of any modern industrial plant, whether achieved by a computer-based system or by conventional means, revolves around *monitor*, *evaluate*, and *act* operations. Transmitters (transducers) measure or 'monitor' the process variables, controllers 'evaluate' the corrective action, and final control elements 'act' on the process. Quality of control depends very much on the quality of measurement.

1.2 EVOLUTION OF PROCESS CONTROL

A historical perspective is invaluable for engineers as it can help in appreciating and finding inexpensive, innovative, and simple solutions to a problem. Process control began centuries ago as a manual art. However, it is only in the past few decades that it has matured into a separate, identifiable field of its own with a solid theoretical basis. At the working level, process control involves the control of variables such as temperature, pressure, flow rate, etc., in processes ranging from oil refining and mineral processing to pharmaceuticals and food processing. However, from a broader planning and management perspective, process control involves maximizing operating profit, guaranteeing product quality, improving safety, and reducing harmful impacts on the environment. Process control is already a key part of almost every process operation and will increase significantly in scope and importance as the full impact of computers, communication, and software technology reaches the process plant level.

Initially, process control mostly revolved around mechanical instrumentation. Transmitters and controllers were mounted directly on the process line which sensed the process conditions with no amplification. Each controller functioned independently, with little or no communication with other controllers. The operator had to move around the plant to adjust set points and note instrument readings.

Increased process complexity and greater demands of plant efficiency and safety called for a centralized mode of operation. As a result, pneumatic amplification and transmission line techniques were developed; allowing the central location of controllers, indicators, and recorders in a control room. Innovative packaging permitted greater number of instruments to be placed on the panel boards. For a long time, pneumatic instrumentation has been the workhorse of the industry, mainly due to the safety it assured in hazardous atmospheres. Efforts to introduce electrical, analog, and electronic instrumentation were slow because explosion-proof instrumentation was difficult to implement and maintain. Further limitation on the part of electronic analogue instrumentation was the need to wire and re-wire hardwired discrete elements upon change in control configuration.

Electronic computers were first applied to process control in 1960s. Due to high cost of digital computers, it was necessary to regulate many control loops of the plant by the computer to justify its initial cost. All process signals were multiplexed, digitized, and stored in memory. Control functions were performed by the software. Control outputs were computed and analog signals were generated which were subsequently transmitted to control valves. This type of computer control is known as direct digital control (DDC). Due to hardware complexity and lack of proven software, the reliability and effectiveness of DDC computer systems were questionable. Moreover, centralized control rooms and high-density panels introduced new problems in signal transmission and necessitated extensive cabling between the process units and the control building. The operator also suffered from visual saturation due to the proliferation of indicators and control devices on the panel board.

Despite these limitations, computers offered the possibilities of integrated control, process optimization, enhanced operator interfaces, data reduction, data storage, and a systematic approach to plant management. To counterbalance the poor reliability of the computer system, analog controllers were added as backup equipment, which further added to the cost of installing a computer control system. It was at this point that the concept of "supervisory control" was introduced. With this arrangement, analog controllers performed the primary loop control. The process computer would monitor the process and adjust the controller set points. This change considerably improved the overall system reliability in comparison to the direct digital approach. The computer was also relieved of some of its computational functions, allowing more CPU time for higher level functions. Cost remained high due to the need for analog instrumentation and panels. Besides, wiring complexity doubled to accommodate the computer. From each analog controller, the process variable, set point, and controlled variable were hardwired to the computer's front-end multiplexer.

Process automation has taken a quantum leap in the last two decades. The advent of microprocessor in early 1970s enabled the application of digital technology to control room instrumentation on a wide scale. At the same time, microprocessors also enhanced the flexibilities and capabilities of digital technology. Microprocessors dramatically reduced the power consumption of computers which made it possible to use many small computers to control the process. These microprocessor-based controllers are located in process areas. A data highway is then routed through the plant to link the controllers together and provide communication with the control room. To provide the operator interface, the process computer or the stand-alone CRT console is connected to the data highway. This distributed approach to process control resulting in distributed control system (DCS) enhanced the reliability and performance of the plant while reducing hardware and installation costs. At the same time, safety techniques and accuracy of electronic field instrumentations touched new heights. DCS is now the backbone of automation.

Process computers, DCS, supervisory control and data acquisition (SCADA), microprocessors, programmable logic controllers (PLC), self-adaptive control, self-tuning control, expert systems, intelligent controllers, fieldbus, smart transmitters, virtual instruments, wireless integrated network sensors, and other forms of digital instrumentation system are the buzzwords of automation—all outcome of the advancement of computer and communication technology. It may be appreciated how technology shifted the workplace from factory to office environment, then from office to home environment. Networking has now made it possible for control engineers to work from home or even while traveling.

1.3 CONCEPT, DEFINITION, AND TYPES OF PROCESS

In process control, the term *process* is used in very general sense and applied to continuous processes. Some examples of typical processes are: energy generation, electric power transmission and distribution systems, chemical and petrochemical industry, metallurgical industry, traffic and transportation systems, paper and pulp processing industry, food and fermentation industry, environmental systems, mining instrumentation, and laboratory equipment production.

Some definitions of the term process are:

- *A series of actions or operations conducing to an end.*
- *A systematic series of operations in production.*
- *A course of operation – natural or artificial.*

The Merriam-Webster's dictionary defines a process to be *a natural, progressively continuing operation of development marked by a series of gradual changes that succeed one another in a relatively fixed way and lead towards a particular result or end; or an artificial or voluntarily progressive operation that consists of a series of controlled actions or movements systematically directed towards a result or end*.

The features of a process are usually measured by process variables. The control of process variables is achieved by controllers (hardware elements or software programs) and final control elements like control valves.

The processes are situated in the production environment and are affected by time-space aspects. These aspects determine the character of the process. The five main process characteristics are: *speed* (slow, fast), *spacing* (lumped, distributed), *continuity* (continuous, discrete), *periodicity* (cyclic, acyclic), and *determinacy* (deterministic, stochastic). Time-space aspects also influence the complexity of a particular process. Processes can further be classified as simple/complex, small/large, natural/artificial, and continuous/batch.

1.4 BENEFITS, DIFFICULTIES, AND REQUIREMENTS OF PROCESS CONTROL IMPLEMENTATION

Process control implementation provided **benefits** like: better regulation of yield resulting in better quality control, better utilization of resources like energy and raw material, higher operating efficiency, increased production, improved reporting and recording of process operations and operator actions, lower costs of production, decreased pollution, and decrease of human drudgery. Operator safety is ensured as the equipments can be controlled sitting remotely at a distant place from isolated and hazardous locations.

There are certain **difficulties** encountered in implementation of process control arising due to the following factors.

Nonlinear and non-stationary nature of process Process gain (resulting in nonlinearity) and/or dynamic parameters (resulting in non-stationary nature) change with the operating point. This causes the process to exhibit highly variable behaviour—sluggish to respond at times, while oscillatory (even unstable) at other times.

Unavailability of accurate measurement of controlled variable In many cases, it is not possible to measure the quantity to be controlled, so it has to be estimated.

Time delays Time delays are encountered in the process and connecting hardware, adding to the difficulty in control.

Multivariable interactions Since multiple variables are being controlled and manipulated simultaneously, interactions among the variables are unavoidable, making the task of control a challenging one.

Sensitivity to noise and disturbances Processes are continuously subjected to various types of known and unknown disturbances and noises which make the task of process control challenging.

There are certain **requirements** which a process/plant has to ensure during its operation, like: quality and quantity of the product, its environmental impact, and safety of personnel and equipment.

Safety Safety of personnel and equipment is of foremost concern. Operating temperatures, pressures, flow rates, concentration of chemicals etc., should not be allowed to exceed allowable limits.

Production specification A plant should produce the desired quantity without compromising with the desired quality.

Environmental regulation In no case, the plant effluents (in the form of solid, liquid, or gas) should exceed the limits decided by federal and state laws. Effluents should not cause air, water, or soil pollution.

Operational constraints The constraints in terms of operating temperature, pressure, level, and flow rates must be adhered to confirm that the product specifications and the safety requirements are not overlooked.

Economics Plant must operate at an optimum level i.e., minimum operating cost and maximum profit. It should be economical in utilization of material, manpower, energy, and capital.

1.5 CLASSIFICATION OF PROCESS VARIABLES

All the process variables can be broadly classified as *input variables* and *output variables*. Input variables convey the effect of surroundings on the process, while output variables convey the effect of process on the surroundings. Further, input variables may be classified *as disturbances or manipulated variables*, while output variables may be classified as *measured or unmeasured variables*. Output variables are the ones to be controlled. The particular variable to be regulated is termed the *controlled variable*. The desired condition of the controlled variable is called the *reference* or *set point*. In case of immeasurable outputs, some other variable is identified which bears definite relationship with the measured output variable. Manipulated variables are the ones which are chosen to affect the change in controlled variable. The selection of manipulated variable depends on how it affects the controlled variable in terms of speed and magnitude. Disturbances can be measurable or immeasurable. Disturbances are also known as *load*; they could arise because of ambient changes or changes in quality and/or quantity of input variables. Figure 1.1 illustrates the classification of process variables.

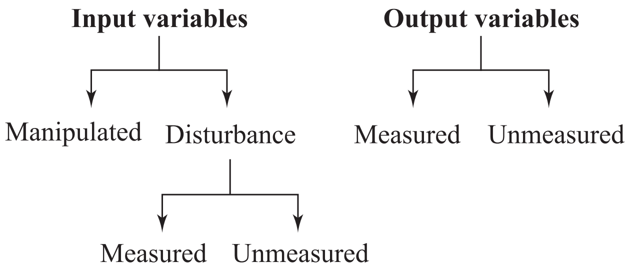

Fig. 1.1 Classification of process variables

Let us take an example of continuously stirred tank heater (CSTH), the schematic representation of which is shown in Fig. 1.2. F_{st} is the steam flow rate; F_i and T_i are the flow rate and temperature of feed respectively. F_o and T_o are the flow rate and temperature of the outlet stream of CSTH. Because of the constant stirring, temperature at the outlet T_o is assumed to be same as the temperature inside the tank(T). Liquid level is denoted by h. Q is the amount of heat added to the CSTH.

Input variables are F_i, T_i, F_{st}, and T_{st}. Output variables are F_o and T_o. F_{st} may be selected as manipulated variable, in which case F_i, T_i, T_{st} are the disturbances. If aim is to maintain T at a particular temperature, then T becomes the controlled variable.

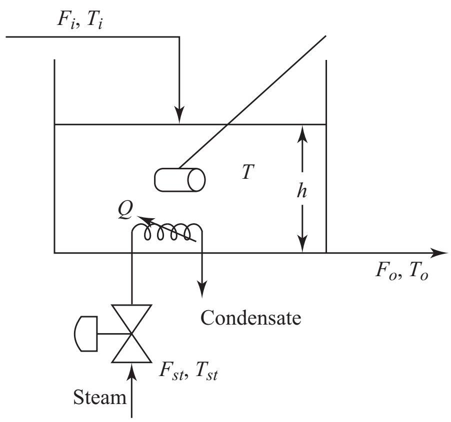

Fig. 1.2 Continuously stirred tank heater (CSTH)

1.6 OPEN-LOOP VS. CLOSED-LOOP SYSTEMS

In a very broad sense, control system can either be a closed-loop system or an open-loop system. In closed-loop system [Fig. 1.3 (a)], the control action is based on measurement of the controlled variable. It usually adjusts the manipulated variables according to the difference between the measured values and the reference values. The closed-loop control system is also called *regulated* or *feedback system*, as it uses the output or result of the system to determine the next input. Closed-loop systems implement functions of *Monitor*, *Evaluate*, and *Control*. The CSTH system discussed above is an example of closed-loop system.

An open-loop control system [Fig. 1.3 (b)] does not utilize the measurement of the controlled variable directly. It has no direct feedback connection. In case of open-loop systems, the value of an input variable is set to a given value with the expectation that it will result in the desired value of the output variable. The actual output and the desired output values are not compared to determine the changes, if any, that the input setting should undergo. A simple example of open-loop system is a room heater without thermostat. Energy input to the heater is not altered automatically to account for the gradual change in room temperature. If we use a temperature transducer to sense the temperature of the room; and compare this temperature with the set-point (desired temperature) before bringing about further change, then it becomes a closed-loop system.

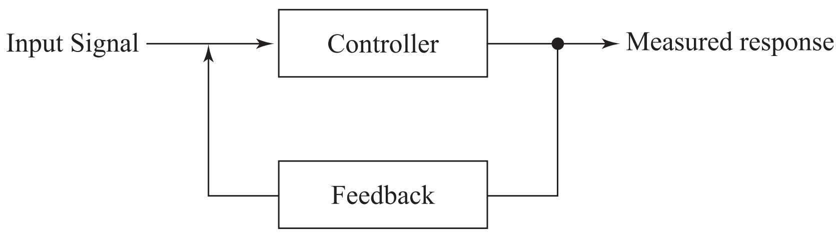

Fig. 1.3 (a) Closed-loop system

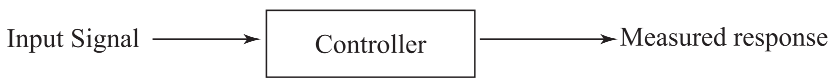

Fig. 1.3 (b) Open-loop system

Closed-loop systems exhibit better performance as they tend to be immune to external disturbances, noise, and parameter variations within the system; resulting in improved quality of control, of course, at an increased cost and complexity. Open-loop systems, on the other hand, are simple and inexpensive, but they cannot correct disturbances and plant variations.

1.7 SERVO VS. REGULATORY CONTROL

Control system essentially ensures the output of a system to behave in a desired way by prescribing an input. Broadly, the objective of control system is one of the following.

- Elimination of disturbances: *Regulatory control*
- Making the controlled variable follow the changes in set point: *Servo control*

1.7.1 Regulatory Control

In this case, deviation of the output from the set point is minimized in the face of changing circumstances by adjusting the inputs to the system. Controlling the temperature in a room in spite of the ambient temperature variation is an example of regulator operation. A regulatory control system will normally have a fixed reference or set point. This does not mean that the set point cannot be changed. Set points do change, but the changes are not very frequent. Set points remain constant for relatively longer periods of time. In regulatory process control systems, load variations usually present the primary problem. Electrical power generation is a typical example of a regulatory system. Reference or set point of 220 V and 50Hz is fixed. The problem is to maintain this set point in spite of continuously changing load demands.

1.7.2 Servo Control

In this case, the aim is to get the output to follow a desired trajectory specified by the input. The problem of controlling the motion of a machine tool according to the shape of a desired template is an example of servo control. In plastic manufacturing process, switching from one grade to another grade with minimum production of off-specification products is an example of "follow up" or "servomechanism".

In servomechanism, the main concern is the determination of controlled variable response according to the changes in reference. A typical example of servomechanism is—numerical control of a milling machine. The reference is continuously changing and the milling cutter must duplicate this change to produce a satisfactory product. In batch control of reactors, after the reactor has been charged with the reactants, a certain temperature-time pattern has to be followed—another example of servo control. In this type of system, few, if any, external or load disturbances affect the system. The Second World War provided the impetus for the development of control theory. The applications were mainly of servo type, for example, tracking of missiles and air crafts, and guiding the direction of space ship. In most servo control applications, the position, speed or acceleration of an object is made to follow the set point closely.

In process control, the focus is mainly on regulator operation, although all closed-loop control systems have provision for carrying out both servo and regulatory control operation.

1.8 FEEDBACK AND FEEDFORWARD CONTROL CONFIGURATION

The primary objective of control system is to suppress or nullify the effect of disturbances on process. Feedback and feedforward are the two basic configurations to achieve this goal and they are differentiated by whether the control action is taken in compensatory or anticipatory manner.

1.8.1 Feedback Control Configuration

Feedback control is the simplest and most widely used configuration in industrial applications. Measuring devices are used to measure the controlled variables and depending upon the difference between desired and measured values, control action is taken to keep the controlled variable at the desired value.

Feedback systems play an important role in modern engineering practice because they have the potential to perform their assigned tasks automatically. Consider the generalized process control loop shown in the Fig. 1.4. It has an output y, a potential disturbance d, and an available manipulated variable m. The disturbance d (also known as load or process load) changes in an unpredictable manner, and control objective is to keep the value of the output y at a desired level. A feedback control action takes the following steps:

1. Measures the value of the output (flow, pressure, liquid level, temperature, composition) using appropriate measuring device. Let y_m be the value indicated by the measuring sensor.
2. Compares the indicated value y_m with the desired value y_{sp} (set point) of the output and finds the deviation (error) $e = y_{sp} - y_m$.
3. The value of the deviation e is supplied to the main controller. The controller in turn changes the value of the manipulated variable m in a way so as to reduce the magnitude of the deviation e. Usually, the controller does not affect the manipulated variable directly but through another device (usually a control valve), known as final control element.

Basic block diagram of the feedback control loop along with the description and symbols of variables and elements is given in Fig. 1.5.

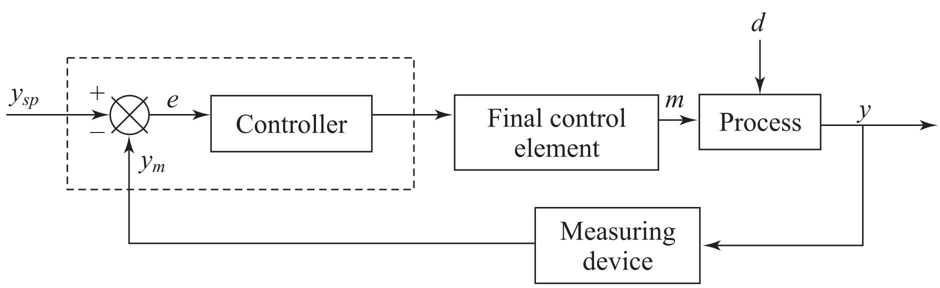

Fig. 1.4 Process control loop involving feedback

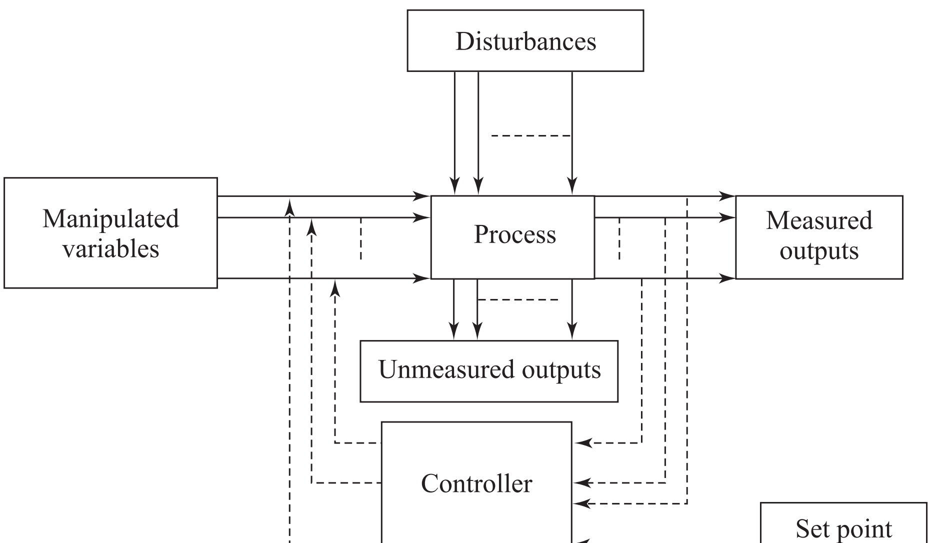

Fig. 1.5 Generalized block diagram of feedback system

Basic feedback loop, both for servo and regulator control, has the objective of making the difference between the desired and controlled variable nearly zero. The advantages of using feedback configuration are:

- Feedback systems do not require identification and measurement of any disturbance since the corrective action takes care of the effect of all the disturbances.
- Due to corrective action, feedback configuration is insensitive to modelling error and parameter changes of the plant.
- Feedback control provides better accuracy, as well as better transient and steady-state response.

The limitations of feedback configuration are:

- It waits until the effect of disturbance hits the process, so it is unsatisfactory for the processes with a large dead time.
- It may also create instability in closed-loop response.
- It is expensive and complex to implement.

1.8.2 Feedforward Control Configuration

Feedforward control measures the disturbances as they enter the process. The configuration uses a controller to adjust manipulated variables so that the effect of disturbances on the controlled variable is reduced or eliminated. Feedforward control acts beforehand in an *anticipatory* manner, while conventional feedback control acts in a *compensatory* manner after the disturbance has affected the system. Feedforward control requires an awareness and understanding of the effect that the disturbance will have on the controlled variable. Feedforward controllers can calculate the exact amount by which the manipulated variables should change to compensate for the disturbances. Feedforward configuration requires an accurate measurement of disturbances. A mathematical relationship of disturbances and manipulated variables with the controlled variables has to be established. Due to these restrictions, feedforward configuration is implemented only in case of well-defined processes. Schematic diagram of feedforward configuration is shown in Fig. 1.6.

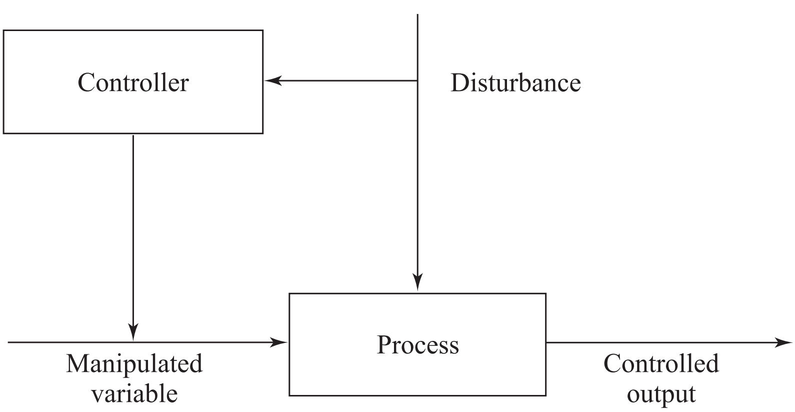

Fig. 1.6 Feedforward control configuration

1.9 STEPS IN SYNTHESIS OF A CONTROL SYSTEM

Designing a control system for a particular requirement involves the following four steps.

Step 1: Translate all operational requirements into control objectives.

Step 2: Identify controlled variables and all relevant measurements.

Step 3: Identify all manipulated variables and disturbances.

Step 4: Determine the best configuration (feedback, feedforward, inferential, cascade, or other loop configuration) that will yield a control system capable of achieving the control objective.

In any control system, the prime objective is to maintain a particular variable at a desired condition, suppressing the disturbances; and at the same time, keeping the system in a stable state. Safety and the adherence to production specifications are the two principal operational objectives of a plant. The next goal is to come out with a plan to make the operation of the plant more profitable.

Optimization of an industrial process usually means increasing profitability without losing sight of safety and product quality. To optimize a material transportation system (pumps, compressors, fans), all the throttling devices have to be opened fully so that all the energy introduced is utilized to transport the material and none of it is spent on overcoming artificially introduced frictional elements such as throttling valves. The optimization of batch reactor might mean to operate it at the minimum cycle period. In continuous chemical reactors, optimization might mean maximized rate of conversion. Optimization, in other words, is a procedure that operates within constraints to reach a well-defined control objective measured by relevant criterion.

Control objectives are first defined qualitatively and then quantified in terms of output variables. To achieve the control objectives, it is required to monitor the process performance by measuring certain variables. Measurement of variables which directly represent the control objectives are known as *primary measurement*. Sometimes, control objectives cannot be translated into measured quantities. In these cases another variable, having a definite relationship with the primary variable, is found out which can be measured easily. Such measurements are called *secondary measurement*. For example, online measurement of concentration is a complex, time consuming, and costly process. That is why, temperature is measured first, and concentration is inferred from it. Similarly, annealed condition of metal is inferred from its temperature.

Selection of manipulated variables out of the possible input variables is a crucial decision which will affect the quality of control. It should be kept in mind that the selected manipulated variables should considerably and readily affect the controlled variable. Control configuration primarily decides how the available measurements should be used to maneuver the manipulated variables. Feedback and feedforward are the two commonly used single loop control configurations.

The two process control laws that lay the ultimate requirements very succinctly are:

- Simplest control system that will do the job is the best.
- You must understand the process before you can control it.

Sophistication in control system is no substitute for process knowledge. However sophisticated a control system may be, it will not work well without proper knowledge of process behaviour.

Example 1.1 A closed-loop control system is used to accurately position components in a production operation. The amplifier-valve positioner part of the system provides 10 mm of displacement per 1 mV change in input. The feedback element provides 0.01 mV per mm change in displacement. What will be the instantaneous error signal when reference signal is suddenly changed by 10 mV?

Solution

$$\frac{\Delta y}{\Delta x} = \frac{G}{1+GH} = \frac{10 \text{ mm/mV}}{1+10 \text{ mm/mV} \times 0.01 \text{ mV/mm}} = 9.09 \text{ mm/mV}$$

For $\Delta x = 10$ mV, $\Delta y = 90.9$ mm

So, error signal = 10.0 – 0.01 × 90.9 = 9.091 mV

Example 1.2 An electrical resistor bears an inverse relationship with temperature. With the increase in current, the temperature increases; this in turn decreases the resistance. Again, as the resistance decreases, the current and temperature increase; and hence, further decrease in resistance. Identify whether this is an example of positive feedback or negative feedback system?

Solution

It is an example of positive feedback, since the current (input) is increased by feedback from the output. Had it been a negative feedback system, the feedback would have brought the input back to its initial value.

Example 1.3 For the RC circuit shown in Fig. E1.3 (a), develop the block diagram relating $E_o(s)$ to $E_i(s)$.

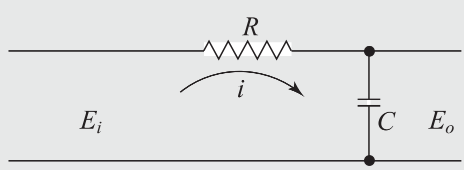

Fig. E1.3 (a) RC circuit

Solution

Systematically developed block diagram has been shown in Figs. E1.3 (b), (c), and (d)

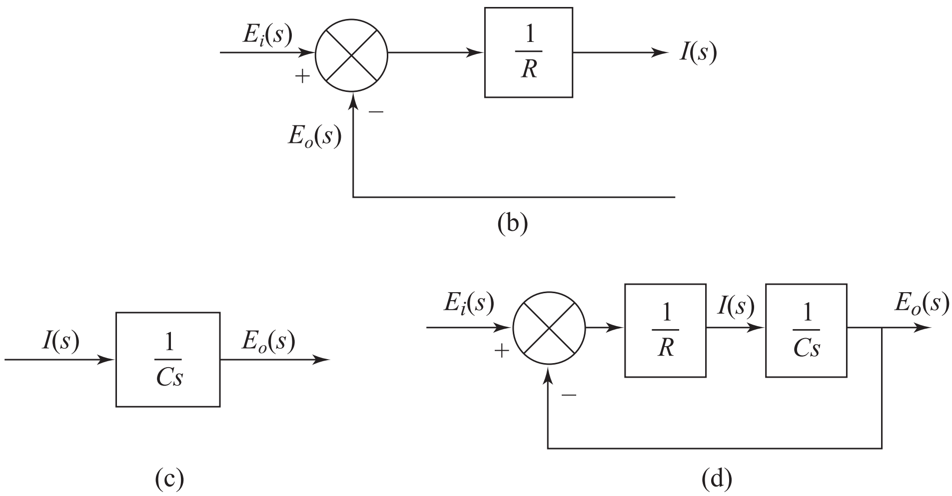

Fig. E1.3 Block diagram

Example 1.4 Figure E1.4 shows a position-control system used with a machine tool, having an amplifier in series with a valve-slider arrangement and a feedback loop with a displacement measurement system. The transfer functions are inside the block. What is the overall transfer function for the control system?

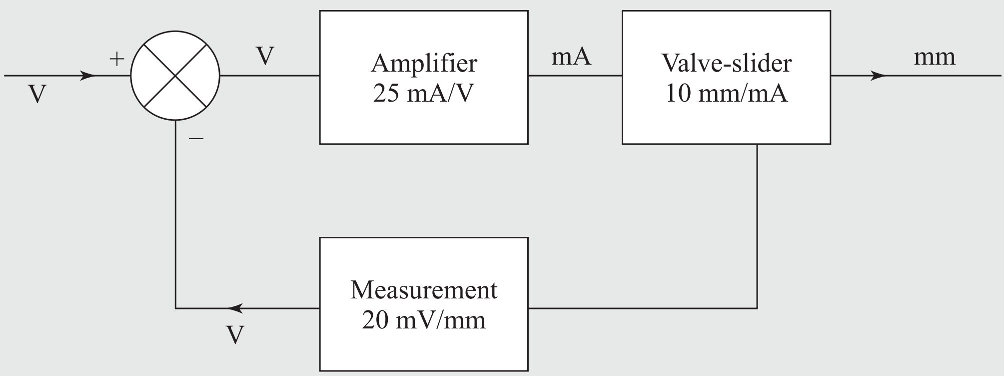

Fig. E1.4 Block diagram

Solution

The amplifier and the valve-slider arrangement are in series, so the combined transfer function (G) for the two elements in the forward path is the product of their separate transfer functions.

$$G = 25\,\frac{\text{mA}}{\text{V}} \times 10\,\frac{\text{mm}}{\text{mA}} = 250\,\frac{\text{mm}}{\text{V}}$$

H is the feedback element having transfer function 20 mV/mm.

$$\textit{Overall Transfer Function} = \frac{G}{1+GH} = \frac{250\,\dfrac{\text{mm}}{\text{V}}}{1 + 250\,\dfrac{\text{mm}}{\text{V}} \times 0.02\,\dfrac{\text{V}}{\text{mm}}} = 41.66\,\frac{\text{mm}}{\text{V}}$$

RECAPITULATION

- Engineering is creativity constrained by cost effectiveness of the product, concerns of safety, environmental impact, ergonomics, reliability, manufacturability, maintainability, and forces of nature.
- Control engineering is the engineering discipline that focuses on the mathematical modelling systems of a diverse nature, analyzing their dynamic behaviour, and using control theory to make a controller that will cause the systems to behave in a desired manner.
- The evolution of process control has been from manual to computer to network control.
- Benefits offered by process control are: improved quantity and quality of production at reduced cost, better utilization of resources like energy and raw material, improved reporting and recording of process operations and operator actions, improved compliant of safety and environmental.
- Difficulties encountered in process control implementation are nonlinear and non-stationary nature of processes, time delays, unavailability of accurate measurement of controlled variable, sensitivity to noise, and disturbances.
- Process variables are classified as controlled variables, manipulated variables, and disturbances.
- Closed-loop systems provide better control than open-loop systems.
- Servo type feedback systems follow the set point changes, while regulatory type feedback systems keep the controlled variable at set point in face of disturbances.
- In feedback control, corrections are carried out before the disturbances affect the output.
- In feedforward control, the necessary corrections are being carried out after the effect of disturbances is felt by the controlled variable.

EXERCISES

Review Questions

1. Explain the concept of *exact* control with the help of an example.
2. With the help of an example, comment upon the statement—"Quality of control can be no better than quality of measurement."
3. What are the typical difficulties encountered during the control of chemical processes?
4. Explain the requirements to be adhered by the process plant during its operation.
5. State the two process control laws. Illustrate with the help of an example.
6. Differentiate between servo and regulator operation with the help of an example.
7. Differentiate between feedback and feedforward operation with the help of an example.
8. "High-fidelity amplifier is an example of servo control". Justify the statement and identify the possible load variables.
9. Differentiate between open-loop and closed-loop system, taking the example of an oven.
10. Synthesize the control system to control the humidity and temperature in a cinema hall. Elaborate each step.

11. Classify the following systems as stable or unstable.
a) Rocking chair b) Pendulum of a wall clock c) A rope-walker in the circus

12. Maneuvering of a geostationary satellite can be categorized as regulator control. Justify the statement.

13. List the four key requirements of a plant that have to be taken care by the process control system.

Numerical Problems

1.1. Replace the capacitor by an inductor in Fig. E1.3 (a) and arrive at the block diagram.

1.2. Figure P1.2 shows the block diagram of a closed-loop speed-control motor. Amplifier-relay-motor system has a combined transfer function of 800 rpm/V and the speed transducer in the feedback path has a transfer function of 5 mV/rpm. What is the transfer function of the total system?

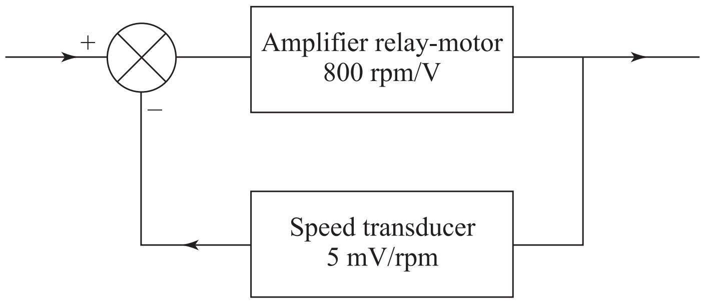

Fig. P1.2 Block diagram

1.3. Figure P1.3 shows the flow rate control system. Calculate the following.

(i) Transfer function for the feedback loop if the transfer function of flow meter and pressure to current converter are $3\ \frac{\text{kPa}}{\text{m/s}}$ and $1\ \frac{\text{mA}}{\text{kPa}}$, respectively

(ii) Transfer function for the forward path if the transfer function of current to pressure converter and control valve are $8\ \frac{\text{kPa}}{\text{mA}}$ and $0.2\ \frac{\text{m/s}}{\text{kPa}}$, respectively

(iii) The overall transfer function of the control system

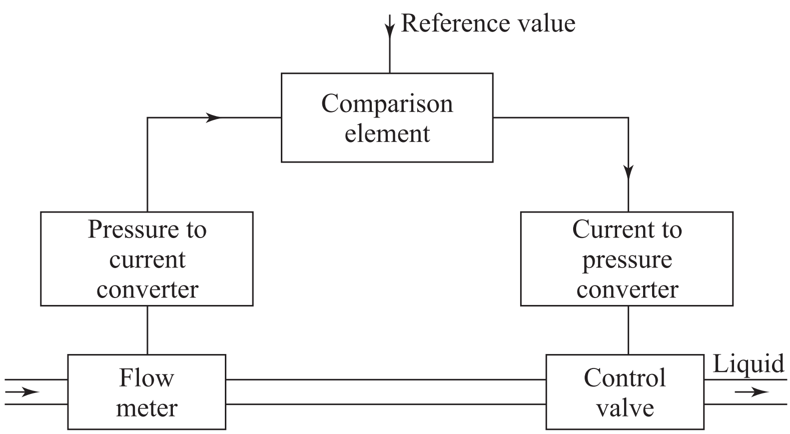

Fig. P1.3 Process diagram