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Introduction

1.1 General introduction

When first encountering the subject of control systems, it should in no way be considered that the topic is a completely new field with which one has had no prior contact whatsoever. In everyday life we encounter control systems in operation and actually perform many controlling actions ourselves. Take, for example, picking up and opening this book, which involves the movement of our hands in a coordinated fashion. This movement is made in response to signals arising due to information obtained from our senses – in this case sight in particular. It is worth mentioning however that the selection of this book, as opposed to other books written by different authors, is an example of the human being behaving as an intelligent control system exhibiting, in this case, signs of good taste and common sense – both of which are difficult properties to quantify and study.

Certain properties are common between many different fields, examples being distance, height, speed, flow rate, voltage, etc., and it is the mere fact of this commonality that has given rise to the field of control systems. In its most general sense a system can be virtually any part of life one cares to consider, although it is more usual for a system to be regarded as something to which the concepts of cause and effect apply. A control system can then be thought of as a system for which we manipulate the cause element in order to arrive at a more desirable effect (if at all possible). In terms of engineering it therefore follows that the study of control systems is multi-disciplinary and is applicable equally well in the fields of chemical, mechanical, electrical, electronic, marine, nuclear, etc., engineering.

Although lying within distinctly different fields, possibly different branches of engineering, systems often exhibit characteristics which are of a similar, if not identical, nature. This is usually witnessed in terms of a system's response to certain stimuli, and although the physical properties of the stimuli themselves can take a different form, the response itself can be characterized by essentially the same information, irrespective of the field in which it lies. Consider, for example, heating a pot of water: this exhibits the same type of exponential response as that witnessed if either a capacitor is charged up or a

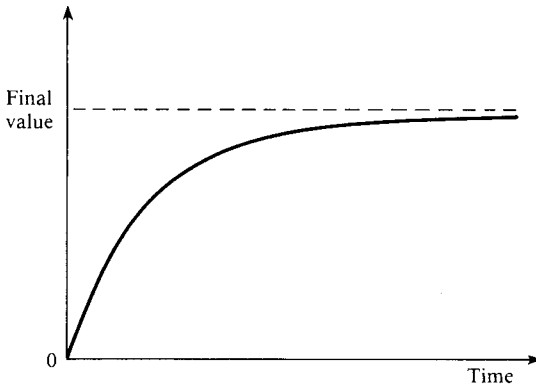


Fig. 1.1 Exponential response of a system

spring is compressed, see Fig. 1.1. The stimulus is, say, quantity of gas (if the water is gas heated), voltage and force respectively; however, the response, whether it be in terms of temperature, charge or stored energy, is still characterized as in Fig. 1.1. The study of control systems in terms of a multi-disciplinary basis therefore means that the results of performance and design tests in one discipline can readily be reposed and re-evaluated within an alternative discipline.

There are essentially two main features in the analysis of a control system. Firstly system modeling, which means expressing the physical system under examination in terms of a model, or models, which can be readily dealt with and understood. A model can often take the form of an appropriate mathematical description and must be satisfactory in the way in which it expresses the characteristics of the original system. Modeling a system is the means by which our picture of the system is taken from its own discipline into the common control systems arena. The second feature of control systems analysis is the design stage, in which a suitable control strategy is both selected and implemented in order to achieve a desired system performance. The system model, previously obtained, is therefore made great use of in the design stage.

The design of a control system only makes sense if we have some objective, in terms of system performance, which we are aiming to achieve. We are therefore trying to alter the present performance of a system in order to meet our objectives better, by means of an appropriate design, whether this is to be in terms of a modification to the system itself or in terms of a separate controller block. Actual performance objectives are very much dependent on the discipline in which the system exists, e.g. achieving a particular level of water or a speed of rotation, although the objectives can be stricter, e.g. requiring that a level of water does not vary by more than 2% from a nominal mean value.

An underlying theme in the study of automatic control systems is the assumption that any required controlling/corrective action is carried out automatically by means of actuators such as electromechanical devices. The concept of a human operative reading a value from a meter and applying what is deemed an appropriate response by pulling a lever or twisting a dial is therefore not really part of the subject matter covered in this

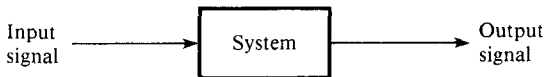


Fig. 1.2 Basic system schematic

book. The human being as an element in a control system is briefly considered later in this first chapter, merely to serve as an example. It is in fact becoming more often the case that a digital computer is employed to turn the measured (meter) value into an appropriate responsive action, the main advantage of such a technique being the speed with which a computer can evaluate a set of what could be complicated equations. It must be remembered however that interfacing is required, firstly to feed the measured value into the computer and secondly to convert the calculated response from the computer into a signal which is suitable for a physical actuator.

In terms of the system under control, an actuator is used to apply a signal as input to the system whereas a suitable measurement device is employed to witness the response in the form of an output from the system. Schematically, a system can therefore be depicted as a block which operates on an input signal in order to provide an output signal. The characteristics of that system are then contained within the block, as shown in Fig. 1.2.

1.2 A concise history of control

To put forward a chronologically ordered set of events in order to show the logical development of a technical subject is certain to be fraught with wrong conclusions and misleading evidence. The study of control systems is certainly no exception in this context, a particular problem being posed by much of the development of the mathematical tools which now form the basis of control systems analysis. It is also a difficult task to point the finger at someone way back in time and accuse them of starting the whole thing. Indeed some historical accounts refer to times well before the birth of Christ for relatively early examples.

As far as automatic control (no human element) is concerned, a historical example cited in many texts is James Watt's fly-ball governor. The exact date of the invention/development seems to vary, dependent on the particular text one is looking at, with dates ranging from 1767 to 1788 being quoted. Although the actual year itself is not particularly important, it serves a primary lesson in control systems analysis not to rely completely on any measured value. James Watt's fly-ball governor is shown in Fig. 1.3, where the control objective is to ensure that the speed of rotation is approximately constant. As the fly-balls rotate so they determine, via the valve, how much steam is supplied; the faster the rotation – the less steam is supplied. The rate of steam supplied then governs, via the piston and flywheel, the speed of rotation of the fly-balls. Although tight limits of operation, in terms of speed variation, can be obtained with such a device,

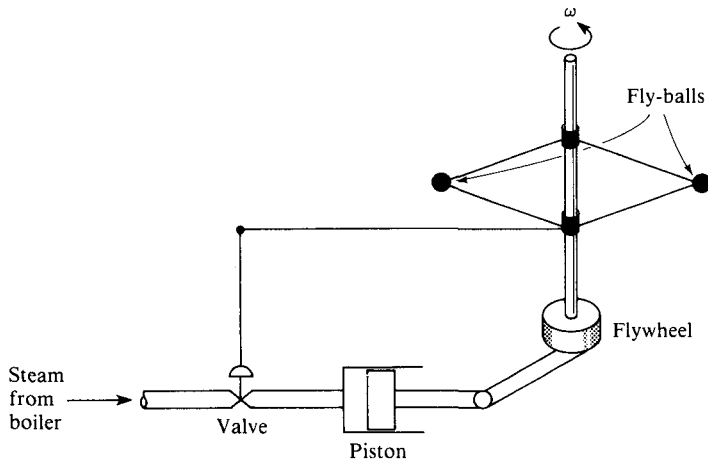


Fig. 1.3 James Watt's fly-ball governor

there are unfortunately several negative features, not the least of these being the tendency of the speed to oscillate about a mean (desired) speed value.

Around 1868, many years after Watt's governor, J. C. Maxwell developed a theoretical framework for such as governors by means of a differential equation analysis relating to performance of the overall system, thereby explaining in mathematical terms reasons for oscillations within the system. It was gradually found that Maxwell's governor equations were more widely applicable and could be used to describe phenomena in other systems, an example being piloting (steering) of ships. A common feature with the systems was the employment of *information feedback* in order to achieve a controlling action.

Rapid development in the field of automatic control took place in the 1920s and 30s when connections were drawn with the closely related areas of communications and electronics. In the first instance (1920s) this was due to analysts such as Heaviside who developed the use of mathematical tools, provided over a century before by Laplace and Fourier, in the study of communication systems, in particular forming links with the decibel as a logarithmic unit of measurement. In the early 1930s Harry Nyquist, a physicist who had studied noise extensively, turned his attention to the problem of stability in repeater amplifiers. He successfully tackled the problem by making use of standard function theory, thereby stressing the importance of the phase, as well as the gain, characteristics of the amplifier. In 1934 a paper appeared by Hazen entitled 'Theory of servomechanisms' and this appears to be the first use of the term 'servomechanism', which has become widely used as a name to describe many types of feedback control system.

The Second World War provided an ideal breeding ground for further developments in automatic control, particularly due to finance made available for improvements in the military domain. Examples of military projects of that time are radar tracking,

anti-aircraft gun control and autopilots for aircraft; each of which requires tight performance achievements in terms of both speed and accuracy of response.

Since that time mechanization in many industries, e.g. manufacturing, process and power generation, has provided a stimulus for more recent developments. Originally, frequency response techniques such as Bode's approach and Laplace transform methods were prominent, along with the root locus method proposed by Evans in the late 1950s. (*Note:* This was also known in the UK at one time as Westcott's method of π lines.) However, in the 1960s the influence of space flight was felt, with optimization and state-space techniques gaining in prominence. Digital control also became widespread due to computers, which were particularly relevant in the process control industries in which many variables must be measured and controlled, with a computer completing the feedback loop.

The 1970s saw further progress on the computer side with the introduction of microprocessors, thus allowing for the implementation of relatively complicated control techniques on one-off systems at low cost. The use of robot manipulators not simply for automating production lines but as intelligent workstations also considerably changed the requirements made of a control system in terms of speed and complexity. The need for high-speed control devices has in the 1980s been a contributing factor too and has made great use of hardware techniques, such as parallel processors, whereas at the same time ideas from the field of artificial intelligence have been employed in an attempt to cope with increased complexity needs. Finally the low cost and ease of availability of personal computers has meant that many control systems are designed and simulated from a software basis. Implementation, which may itself make use of a computer, is then only carried out when good control is assured.

1.3 Open-loop control

An open-loop control system is one in which the control input to the system is not affected in any way by the output of the system. It is also necessary however that the system itself is not varied in any way in response to the system output.

Such a definition indicates that open-loop systems are in general relatively simple and therefore often inexpensive. An excellent example is an automatic electric toaster in which the control is provided by means of a timer which dictates the length of time for which the bread will be toasted. The output from the toasting system is then the brownness or quality of the toast, the assumption being that once the timer has been set the operator can only wait to examine the end product.

Clearly the response of an open-loop system is dependent on the characteristics of the system itself in terms of the relationship between the system input and output signals. It is apparent therefore that if the system characteristics change at some time then both the response accuracy and repeatability can be severely impaired. In almost all cases however the open-loop system will present no problems insofar as stability is concerned,

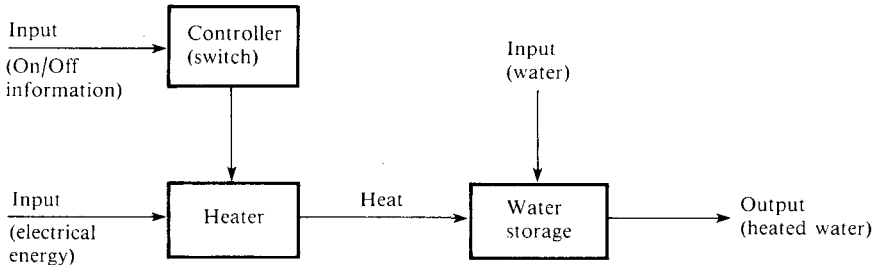


Fig. 1.4 Water heating device

i.e. if an input is applied the output will not shoot off to infinity – it is not much use as an open-loop system if this is the case.

Another example of an open-loop system is the water heater shown in Fig. 1.4, in which the controller is merely an on/off switch which determines when the heater is supplying heat in order to provide heated water at a certain specified temperature.

A problem with this open-loop system is that although today the water may be provided at a nice temperature at the output, tomorrow this might not be the case. Reasons for this could be a change in ambient conditions, a change in the temperature or amount of water input to the storage device or a drop in the voltage used to supply the heater. Merely leaving the system as it is and hoping for the best is clearly not satisfactory in the majority of cases. It would be much more sensible to measure the temperature of the heated water such that the on/off information can be varied appropriately in order to keep the output at approximately the temperature desired. We have now closed the loop, by providing feedback from the system output to an input, hence the system is no longer open-loop, but rather is closed-loop.

1.4 Closed-loop control

In a closed-loop system the control input is affected by the system output. By using output information to affect in some way the control input of the system, feedback is being applied to that system.

It is often the case that the signal fed back from the system output is compared with a reference input signal, the result of this comparison (the difference) then being used to obtain the control or actuating system input. Such a closed-loop system is shown in Fig. 1.5, where the error = reference input – system output.

Very often the reference input is directly related to the desired value of system output, and where this is a steady value with respect to time it is called a set point input.

By means of the negative feedback loop shown in Fig. 1.5 (negative because the system output is subtracted from the reference input) the accuracy of the system output in relation to a desired value can be much improved when compared to the response of an open-loop system. This is simply because the purpose of the controller will most likely be

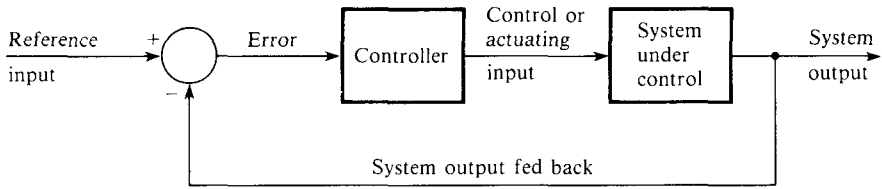


Fig. 1.5 Closed-loop system

to minimize the error between the actual system output and the desired (reference input) value.

A disadvantage of feedback is related to the fly-ball governor of Fig. 1.3, where oscillations can occur in the system output, the speed of rotation, which would not occur if the system were connected in open-loop mode. The oscillations are due to the attempt to get the error signal to as low a magnitude as possible, even if this means swinging the output first one way and then the other.

The open-loop heating system of Fig. 1.4 can be converted into a closed-loop system by measuring the temperature of the heated water (output) and feeding this measurement back such that it affects the controller by means of modifying the switch on/off information. It is then apparent that when variations in performance occur due to system modifications or a change in ambient conditions, the effect on the system output will be much reduced because of the feedback arrangement, i.e. with feedback the system is less sensitive to variations in conditions. Let us assume that we require the water temperature to be 50°C . With the system in open-loop, a variation in system characteristics would merely cause the temperature to drift away from the required value. With the system in closed-loop however, any variation from 50°C will be seen as an error when the actual measured temperature is compared with the required value, and the controller can then modify the control input in order to reduce the error to zero.

1.4.1 Effects of feedback

Open-loop systems rely entirely on calibration in order to perform with good accuracy; any system variations or effects caused by outside influences can seriously degrade this accuracy. Although only common in relatively simple systems, an important property is found in that an increase in system gain (amplification) does not affect the stability of an open-loop system (oscillations cannot be induced in this way).

Once feedback is applied, the system is in closed-loop. Closed-loop systems can achieve much greater accuracy than open-loop systems, although they rely entirely on the accuracy of the comparison between desired and actual output values and therefore on the accuracy of the measured output value. Effects of system variations or outside influences are much reduced, as are effects due to disturbances or nonlinear behavior. Unfortunately the advantages obtained when feedback is employed are at the expense of system stability (oscillations can often be induced by increasing system gain).

1.5 Some examples of control systems

Many simple control systems in everyday life include a human being, not only in the feedback loop but also to provide the actuating signals and even as the control system itself. Consider drinking a cup of coffee, which involves lifting a cup through a desired height. Feedback is provided via touch and sight, with a comparison being made between where the cup actually is at any time and where we want it to be, i.e. by our mouth – this is the error signal. An actuating signal is then provided in terms of lifting the cup with our hand at a rate which is dependent on how large the error signal is at any time. Performance is measured in terms of how quickly we can lift the cup – lifting it too quickly or going past the desired end position will result in coffee being spilt and possibly several broken teeth, conversely lifting it too slowly will result in severe boredom and even death through lack of liquid intake. This is really an example of a *biological control system*, everything within the system, except the cup and coffee, being part of the human being.

Note that outside influences such as windy weather, a lead weight in the bottom of the cup or the temperature of the coffee have not been considered. Although all of these would affect the performance in question, they were considered to be outside the scope of the system definition in the first instance. This is an important initial point because when modeling a control system the more characteristics that are included in the model, the more complex that model becomes. A trade-off therefore has to be made in terms of model complexity and the ability of that model to account for all eventualities. It would not be sensible to include the effect of high winds when modeling the act of drinking a cup of coffee because the vast majority of cups of coffee are not drunk in the presence of high winds.

Often the human being merely forms part of an overall control system, examples being driving an automobile and cooking, where the human can merely form the feedback loop – measuring the actual output, comparing this with the desired value and then modifying the control input accordingly.

Many control systems have been automated by replacing the human feedback element with more accurate equipment which also responds more rapidly. Examples of this are *ship steering* and *flight control*, for which pilots are replaced by autopilots whereby information from sensors, such as roll detectors and gyros respectively, is used to ensure constant velocity and constant heading. Any change in either of these requirements can be fed in merely as a change in set-point value. Taken further, both *ship docking* and *aircraft landing* can also be automatically carried out, by means of computational procedures either operating *in situ* or from a remote station. These latter examples serve as particular reminders that many different characteristics must be taken into account when modeling a system; neglecting the effect of rough weather or the presence of other craft could be fatal in this instance.

Other transit systems also employ automatic control techniques; certain automatic electric trains fall into this category along with autonomous guided vehicles (AGVs) which are not restricted to operation along certain lines, such as rails. With both visual

(camera) and distance (laser and sonar) information it is now possible for these vehicles to 'drive' themselves and it should not be long before greater use is made of such techniques in automobiles. The military interest in such vehicles is important for their development, as indeed it is for future developments in gun positioning, radar tracking and missile control, all of which involve rapid tracking of a target, with minimum error.

In manufacturing, *automated production lines* are not only supervised by an overall automatic controller, but each individual workstation can consist of a robot manipulator which either merely performs a set routine repeatedly with good accuracy and speed or which modifies its actions due to visual and/or tactile information feedback. On a similar basis the control of *machine tools* is gradually increasing in complexity from simple profile copying mechanisms, through numerical control for exact coordination, to machine tools which can modify their procedure in response to varying conditions such as differing workpiece requirements.

Power generation is also an important area in the application of automatic control systems. *Nuclear reactor control* is concerned with the rate at which fuel is fed into the reactor and it is in areas such as this that the effects of hazardous environment must also be taken into account. Certainly the large number of variables which need to be measured in order to provide a useful picture of the system presents many problems in terms of accuracy and reliability. Indeed other systems concerned with power generation and distribution share many instrumentation difficulties. Stricter controls imposed due to *environmental pollution* have meant not only increased efficiency requirements in the conversion schemes themselves but also the use of automatic control devices to control effluence.

Further down on the electrical power scale, *voltage stabilizers* are employed to retain the output voltage from a source as close as possible to a reference voltage value. This is done by comparing the actual voltage output with the reference, any difference (error) then being used to vary the resistance provided by a transistor which is connected in series with the source.

Uniformity in the thickness of such as paper, steel and glass is based on the control of the motor speed of rollers and drawing machines. Rollers are often not perfectly cylindrical and, combining this with possible large variations in the product quality (e.g. pulp obtained from a different factory), *controlling output thickness within tight limits* is not a simple task. Letting the thickness increase merely wastes money whereas letting it decrease produces an inferior product, hence tight limits are necessary. The control of *motors* both in terms of position and speed is however a much wider field than mentioned here, the complexity of control being dependent on the accuracy requirements made.

In terms of financial outlay, large amounts have been spent in providing accurate automatic systems for *process control*. In oil and chemical industries a small percentage improvement in reducing output variations (e.g. flow rate, concentration) in many cases results in millions of dollars being saved. Process plants are usually characterized as fairly slowly varying systems with only occasional changes in reference input. Controllers are required in order to minimize the effect of disturbances on the output signal. *Biochemical control* and *biomedical control* are in most cases closely related to process

control systems, with the former including such examples as drug production and fermentation, and the latter respiratory monitoring and pain relief.

Automatic control has become increasingly more important in *agricultural engineering*, with intelligent tractors now able to cope with wheel slip and to provide a constant ploughing level despite surface variations. Improved automobile *engine performance* and efficiency has become more and more dependent on complex control schemes, with power generated by means of the engine itself being used to provide energy for the electronic/microcomputer-based control circuitry.

Obvious advantages can be obtained by successfully modeling *economic systems* in order to obtain suitable automatic control schemes. Apart from the most simple cases however it is extremely difficult to account for many of the spurious events that can occur in practice and which have considerable effect on the economic system under control, an example being the price of shares on the stock market. *Social systems* are similar to economic systems in terms of modeling difficulties and also suffer from the fact that very often there are both a large number of outputs and also different measures of performance which are often contradictory.

Hopefully a good idea of the wide variety of system types in which automatic control schemes operate has been given. When one is new to the subject, examples encountered are often related to relatively simple applications with which the reader may be familiar, e.g. electromechanical systems, electronic amplifiers, chemical plant, mechanical systems and electrical machines. It should be remembered that many of the simple techniques considered remain as simple techniques even when applied to the most complicated plant.

1.6 Definitions of standard terminology

As with most subject areas, terminology is used in the study of control systems which aptly describes phenomena within the field. It can, however, be seen as rather vague and in many cases confusing from the outsider's point of view. A list of definitions is therefore given here in order to help remove any barriers which do exist (see Fig. 1.6).

1. Lower case letters refer to signals, e.g. voltage, speed; and are functions of time, $u = u(t)$.
2. Capital letters denote signal magnitudes, as in the case of $u(t) = U \cos \omega t$, or otherwise Laplace transformed quantities, $U = U(s)$. Where $s = j\omega$, this is indicated by $U(j\omega)$.

Note: s is the Laplace operator and $\omega = 2\pi f$ where f is frequency.

3. The system under control is also known as the *plant* or *process*, G .
4. The *reference input*, v , also known as the set-point or desired output, is an external signal applied in order to indicate a desired steady value for the plant output.
5. The *system output*, y , also known as the controlled output, is the signal obtained from the plant which we wish to measure and control.

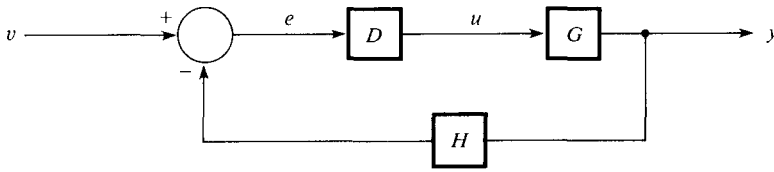


Fig. 1.6 Closed-loop system with feedback element H

6. The *error signal*, e , is the difference between the desired system output and the actual system output (when $H = 1$).
Note: See 8.
7. The *controller*, D , is the element which ensures that the appropriate control signal is applied to the plant. In many cases it takes the error signal as its input and provides an actuating signal as its output.
8. The *feedback element* H provides a multiplying factor on the output y before a comparison is made with the reference input v . When $H \neq 1$ the error e is the error between v and Hy , i.e. it is no longer the error between v and y .
Note: Often $H = 1$, although H can represent the characteristics of the measurement device in which case most likely $H \neq 1$.
9. The *feedback signal* is the signal produced by the operation of H on the output y .
10. The *control input*, u , also known as the actuating signal, control action or control signal, is applied to the plant G and is provided by the controller D operating on the error e .
11. The *forward path* is the path from the error signal e to the output y , and includes D and G .
12. The *feedback path* is the path from the output y , through H .
13. A *disturbance*, or noise (not shown in Fig. 1.6), is a signal which enters the system at a point other than the reference input and has the effect of undermining the normal system operation.
14. A *nonlinear* system is one in which the principles of superposition do not apply, e.g. amplifier saturation at the extremes, or hysteresis effects. Almost all except the most simple systems are nonlinear in practice, to an extent at least. The vast majority of systems can however be dealt with by approximating the system with a linear model, at least over a specific range.
15. A *time-invariant* system is one in which the characteristics of that system do not vary with respect to time. Most systems do vary slowly with respect to time, e.g. ageing, however over a short period they can be considered to be time-invariant.
16. A *continuous-time* system is one in which the signals are all functions of time t , in an analog sense.
17. A *discrete-time* system is a system such as a digital system or a sampled data system in which the signals, which consist of pulses, only have values at distinct time instants. The operator z is used to define a discrete-time signal such that $z^3 y(t) = y(t + 3)$ means the value of signal $y(t)$ at a point in time three periods in the future, where a period T (sample period) is defined separately for each system.

18. A *transducer* converts one form of energy (signal) into another, e.g. pressure to voltage.
19. *Negative feedback* is obtained when $e = v - Hy$.
20. *Positive feedback* is obtained when $e = v + Hy$.
Note: This is not shown in Fig. 1.6.
21. A *regulator* is a control system in which the control objective is to minimize the variations in output signal, such variations being caused by disturbances, about a set-point mean value.
Note: A regulator differs from a servomechanism in which the main purpose is to track a changeable reference input.
22. A *multivariable* system is one which consists of several inputs and several outputs. In this text only single variable systems are considered.

1.7 Summary

In this first chapter the purpose has been to gently introduce the subject area of control systems, by providing a brief historical account of developments leading to its present state and also by putting forward the idea of feedback control in terms of some elementary forms. To do this it has been necessary to employ representative diagrams to show connections between signals and systems. These diagrams are described in much greater detail in the following chapter.

Many examples of the application of control systems were given in an attempt to show the multi-disciplinary nature of the subject. Once the fundamentals of a particular control technique have been studied in one field, they are generally applicable in many other fields. Control engineers therefore come from many different backgrounds in terms of subjects studied and an even more diverse set exists in terms of areas in which a control engineer can show a certain amount of understanding.

In the chapters which follow many techniques are shown for the modeling, control and study of system behavior. The ideas put forward should not be seen as limiting or restrictive in any way, in terms of applications, but rather as an insight to the wide variety of possibilities.

Problems

- 1.1 A thermostat is often used in order to control the temperature of a hot water tank. If the water is heated from cold, explain, with the aid of a sketch of water temperature versus time, the principle of operation of such a device. Why is a simple open-loop system not used instead?
- 1.2 Explain the open-loop operation of traffic signals at a road crossing. How can improved traffic control be achieved by means of a closed-loop scheme?

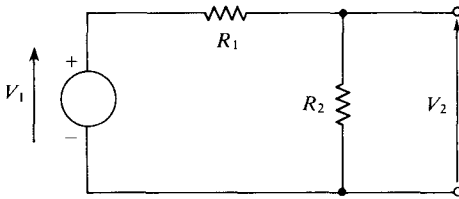


Fig. 1.7

- 1.3 Consider a missile guidance system which is based on an open-loop scheme, once the missile has been launched. How can a closed-loop technique be devised in order to track a target and what problems can this cause?
- 1.4 Consider the potential divider in Fig. 1.7. The output voltage is V_2 and the input voltage is V_1 .
How can the system be both an open- and closed-loop system at the same time?
- 1.5 The population of rabbits in a particular field is unaffected by events external to the field, including visiting rabbits. The population consists of adult males, adult females and young rabbits.
Each year 20% of adult males and females die, while the number of newborn young which survive to the following year is twice the number of adult females alive throughout the present year.
Each year 40% of the young become adult males the following year and 40% of the young become adult females the following year. Meanwhile, the remaining 20% of the young die.
Find equations to describe each section of the population from one year to the next.
- 1.6 Consider the simplified economic system describing the price of a toy. Demand for the toy will decrease if the price of the toy increases, whereas supply of the toy increases if its price increases. By finding the difference between supply and demand, show how this can be used as an error signal to effect a controlling action on the price.
- 1.7 Foxes move into the field inhabited by the rabbits of Problem 1.5, and use the rabbits as a food source. F is the number of foxes at any one time and R is the number of rabbits. The rate of change of foxes is equal to a constant K_1 multiplying the error between R and a number \bar{R} , whereas the rate of change of rabbits is equal to a constant K_2 multiplying the error between a number \bar{F} and F .
How does the system operate; what happens to F and R with respect to time?
- 1.8 Consider the end effector of a robot manipulator. Explain how, in many cases, this is operated in open-loop mode. How could a closed-loop system be constructed for the manipulator?
- 1.9 In a liquid level system, what problems could occur if an open-loop scheme is employed? Can all of these problems be removed by employment of a

closed-loop technique? Are any problems brought about due to the closed-loop format itself?

- 1.10 Consider driving a vehicle without using any feedback, e.g. close your eyes and ears and drive (maybe you drive this way already!).

What advantages are obtained if a closed-loop vehicle driving scheme is used, which includes a human operator? (obvious answers). How could the vehicle driving scheme be configured without a human operator? Are there any particular advantages or disadvantages to such a technique?

Further reading

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