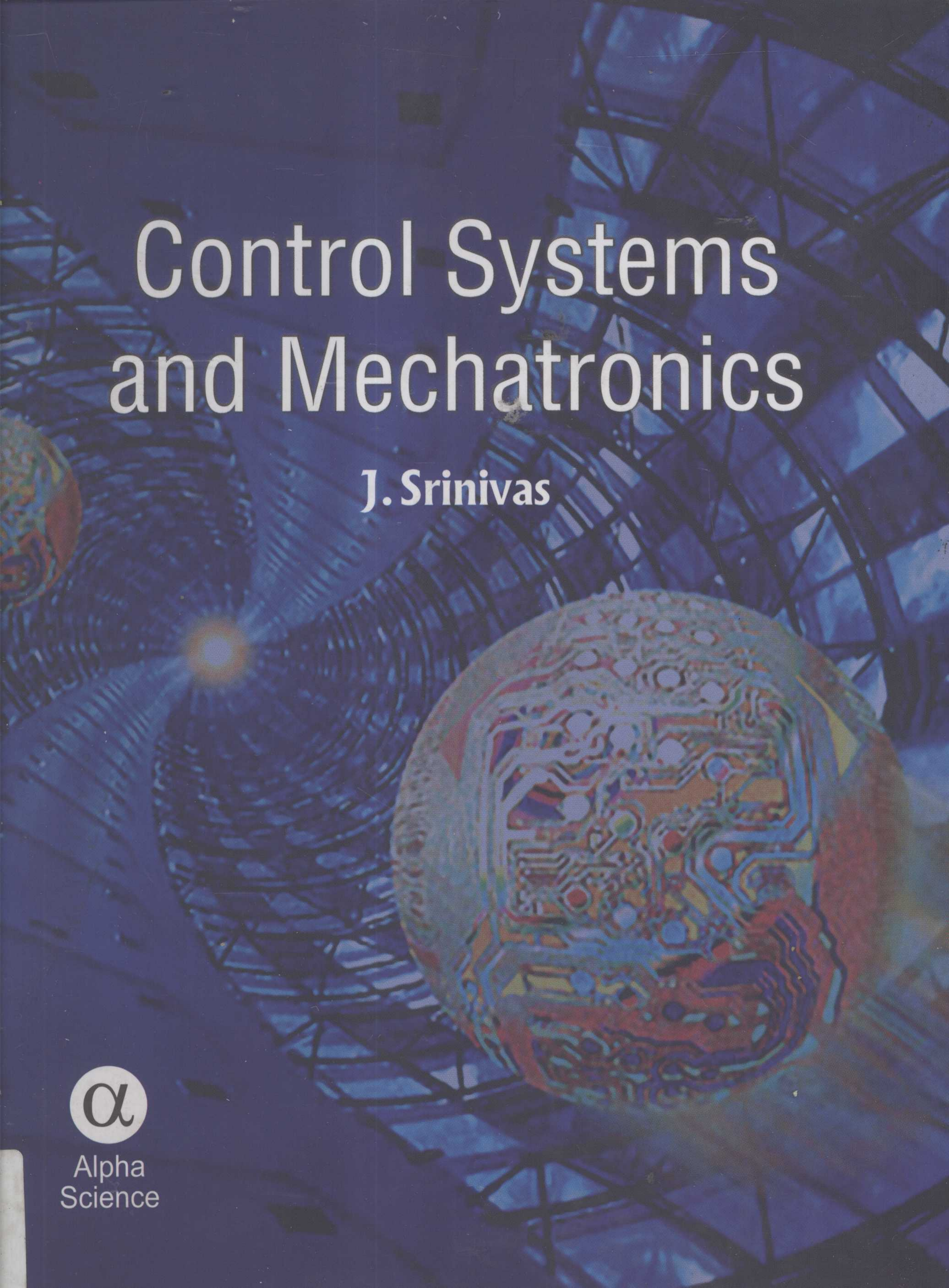
Control Systems and Mechatronics

J. Srinivas



Alpha Science

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www.alphasci.com

ISBN 978-1-84265-439-2

Printed in India

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Preface

Control systems have found a broad range of applications in the areas like electrical, mechanical, aerospace and chemical engineering. Use of control systems is found over wide range of situations in daily life. The study of control system engineering is essential for practical implementation of real time controllers. The field of design and analysis of control systems has been increased to nonlinear control and optimal control. This book tries to present theory and practical applications of control systems. Basic background needed for the reader in understanding this book is the knowledge of differential equations, Laplace transforms and linear algebra. This basic course is organized here into eleven chapters, including digital, nonlinear controls and mechatronics.

Chapter - 1 describes an introduction to control systems and effects of feedback on system performance. Concept of transfer function is also presented.

Chapter - 2 presents basic building blocks of control systems like block diagrams, signal flow graphs and state space analysis. Several simple illustrations make the readers interesting.

Chapter - 3 gives the concept of physical modeling of several control systems like mechanical, electrical, electromechanical, thermal and liquid level systems. Good number of applications is also given.

Chapter - 4 explores with the time domain performance analysis, using standard excitations like step, ramp and parabolic. Basic second order system is considered in detail. Design of control system with specifications of error constants is also given. Concept of proportional, derivative and integral controls have been also presented.

Chapter - 5 discusses the aspect of stability of a control system with Routh-Hurwitz criteria. Relative stability analysis approach is presented in a lucid style.

Chapter - 6 presents the analysis of control system in frequency domain. Frequency domain specifications are described. Frequency domain techniques like Nyquist plot, Bode plot, Nichol's chart are presented with examples. Basic root locus technique for analysis is also given. Several solved problems help in understanding the subject more effectively. The concept of compensators is also presented.

Chapter - 7 describes the digital control systems mathematically. Physically realizable control system concepts are given here.

Chapter - 8 explores the nonlinear control systems, with various types of built-in nonlinearities, like hysteresis, backlash etc. Methods of analysis of nonlinear systems are presented with examples.

Chapter - 9 describes fundamental concepts of mechatronics. A practical digital controller can be best developed with thorough knowledge of interfacing devices with sensors and actuators. Electronic sensors like optical encoders in control systems are explained in basic level. Concepts of microcontrollers and programmable controllers are given briefly.

Conducting experiments in Mechatronics Laboratory is a vital job. In this regard, few study experiments are presented in Chapter-10. These experiments would summarize the basic electronics by observing the concerned devices in the laboratory. Chapter-11 describes some more practical experiments relating to programmable controllers and simulators over specific type of equipment and software. MATLAB, SIMULINK as well as Pneumatic and Hydraulic simulators would help in understanding the controller performance and modeling the system using simple programs and graphic elements. I am acknowledging the Mechatronics Laboratory of Sri Chandra Sekharendra Saraswathi Viswa Maha Vidyalaya, Kanchipuram.

Introduction to Laplace transforms, which are often required in this course, has been given in the Appendix. Also simple computer programs for obtaining response histories and for drawing Bode plots are presented at the end of the book. A list of common laboratory experiment in Mechatronics and basic built-in commands for MATLAB control systems toolbox is also reported in appendices.

A glossary of terms in control systems is provided at the end of the book.

I sincerely thank the publishers in bringing the book in a nice format. I am also grateful to all those involved in compiling this book, specifically Dr. M. Ananda Rao, Dr. Hun sun Yang, Dr. Dukkipati. Finally I acknowledge the unforgettable involvement and encouragement given from my family members. Any suggestions for improvement and typographical mistakes are always cherished and will be gratefully acknowledged.

J. Srinivas

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1

Introduction

Control system is concerned with understanding and controlling the process governed by any system to accomplish an objective. In the most abstract sense, it is possible to consider every physical object as a control-system. The word control means to regulate, direct or command. A system is an arrangement of physical components connected or related in such a manner as to form or act as an entire unit. Thus control system is an arrangement of physical components connected or related in such a manner as to command, direct or regulate itself or another system. In practice, everything alters its environment in some manner like a mirror directing a beam of light shining on it at some acute angle, where the mirror may be considered as elementary control system controlling the beam of light. In engineering science, the meaning of control-systems is usually restricted to those systems whose major function is to dynamically or actively command, direct or regulate. The excitation or stimulus applied to a control-system from an external energy source is usually termed as input and the actual response obtained from a control system is known as output. The output may or may not be equal to the specified response implied by the input. The purpose of control-system usually is to identify or define the output and input. If the output and input are given, it is possible to identify or define the nature of the system's components. Control systems may have more than one input or output. By the system description, often all input and outputs are well defined. But sometimes they are not. For example, radio receptions get intermittently interfered with atmospheric electric storm and produce an unwanted output from a loudspeaker. This noisy output is not usually specified for the simple identification of a radio-receiving system, but is part of the total output. For the purpose of simply identifying a system, spurious inputs producing undesirable outputs are not normally considered as inputs and outputs in the system description. But it is usually necessary to carefully consider these extra inputs and outputs when the system is examined in detail. Broadly there are 3-basic types of control systems:

(a) Man-made control systems
(b) Natural, including biological-control systems
(c) Control systems whose components are both man-made and natural.

An electric switch is a man-made control system controlling electricity-flow. Simple act of pointing at an object with a finger requires a biological control system consisting chiefly of eyes, the arm, hand and finger and the brain of a man, where the input is precise-direction of the object with respect to some reference and the output is the actual pointed direction with respect to the same reference. The control system consisting of a man driving an automobile has components which are clearly both man-made and biological. The driver wants to keep the automobile in the appropriate lane of the roadway. He accomplishes this by constantly watching the direction of the automobile with respect to the direction of road. Fig. 1.1 shows the basic entities in general control system.

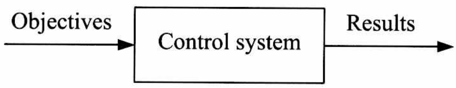

Fig. 1.1 Components of a control system

None of the systems in universe can be imagined without control. Fly ball governor is a first automatic mechanical control for controlling the speed of steam engine. Speed is controlled by movement of ball, which controls the motion of valve for steam output. Before this invention, other feedback systems invented namely 'water level float regulator'. The float detects the water level and controls the valve, which in turn controls the water entering the boiler. In steering control of an automobile for example, the direction of two front wheels can be regarded as the result or controlled output variable and the direction of the steering wheel is actuating signal or objective. The control-system in this case is composed of the steering mechanism and the dynamics of the entire automobile. As another example, consider the idle-speed control of automobile engine, where it is necessary to maintain the engine idle speed at a relatively low-value (for fuel economy) regardless of the applied engine loads (like air-conditioning, power steering, etc.). Without the idle-speed control, any sudden engine-load application would cause a drop in engine speed that might cause the engine to stall. In this case, throttle angle and load-torque are the inputs (objectives) and the engine-speed is the output. The engine is the controlled process of the system. Some more applications of control-systems can be found in print wheel control of an electronic type writer, a thermostatically controlled heater or furnace which automatically regulates the temperature of a room or enclosure, sun tracking control of solar collector dish.

Control systems are classified into two general categories: open loop and closed-loop systems. The distinction is determined by the control-action, which is responsible for activating the system to produce the output. An open-loop system is one in which the control action is somehow dependent on the output. An automatic toaster is an open-loop control system because it is controlled by a timer. Open-loop control systems are not generally troubled with problems of instability. Their ability of accuracy-performance is determined by calibration. Fig. 1.2 illustrates a simple tank-level control system. To hold the tank level h within reasonable acceptable limits even though the outlet flow through valve V_1 is varied, the inlet flow rate can be adjusted by irregular manner using valve V_2.

Figure 1.3 shows the simple relationship that exists in this system between the input (the desired tank level) and the output (the actual tank level) . This signal flow representation of the physical system is called a *block-diagram.*

Arrows are used to show the input entering and the output leaving the control system. Thus this system does not have any feedback comparison.

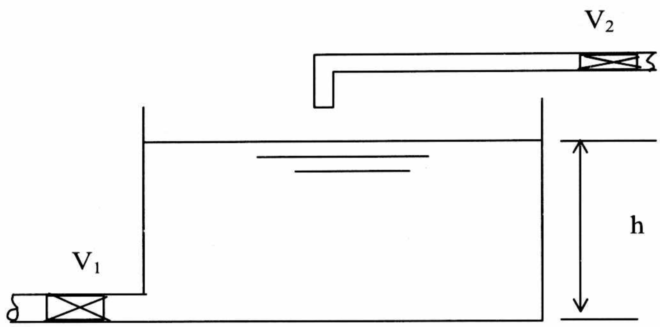

Fig. 1.2 Simple tank level control system

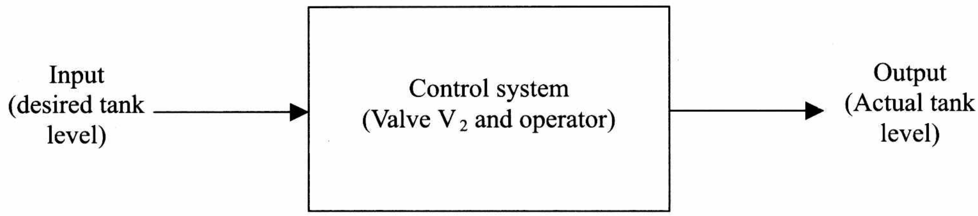

Fig. 1.3 Block diagram of open loop system

An auto-pilot mechanism and the airplane controls come under a closed-loop control system. Closed-loop systems are commonly called *feedback-control* systems. They derive their valuable accurate reproduction of the input from feedback comparison. An error detector derives a signal proportional to the differences between the input and output. Two approaches for analyzing the system were developed: (a) frequency domain approach and, (b) time domain approach. Thus a control system prompts the performance of any plant or system towards the accuracy and gives the desired result, with high speed within stability limits and with minimum influence of noise and disturbances on the result.

Example 1.1: Identify the input and output for an automatic washing machine.

Solution: Many washing machines operate in the following manner. After the clothes have been put into the machine, the soap or detergent, bleach and water are entered in the proper amounts. The wash and spin cycle-time is then set on a timer and the washer is energized. When the cycle is completed, the machine shuts itself off. If the proper amounts of detergent, bleach and water and the appropriate temperature of the water are predetermined or specified by the machine manufacturer or automatically entered by the machine itself then the input is time for the wash and spin cycle. The timer is usually set by a human operator.

The output of a washing machine is more difficult to identify. Let us define clean as the absence of foreign substances from the items to be washed. Then we can identify the output as the percentage of cleanliness. At the start of a cycle the output is less than 100% and at the end of a cycle the output is ideally equal to 100%. In this case, adjusting the amounts of detergent, bleach, water and the temperature of water can control the percentage of cleanliness. All these quantities may be considered as inputs.

1.1 FEEDBACK SYSTEMS

Feedback control systems more or less lead to automation. Fig. 1.4 illustrates automatic tank-level control mechanism.

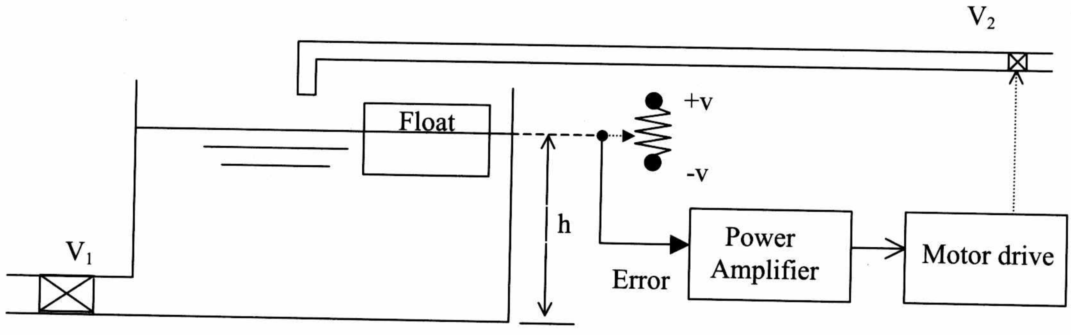

Fig. 1.4 Automatic tank level control

It can maintain the desired tank level *h* within quite accurate tolerances even though the output flow-rate through valve V_1 is varied. If the tank level is not correct, an error voltage is developed. This is amplified and applied to a motor drive, which adjusts valve V_2 in order to restore the desired tank-level by adjusting the inlet flow rate. A block-diagram analogous to this system is shown in Fig. 1.5.

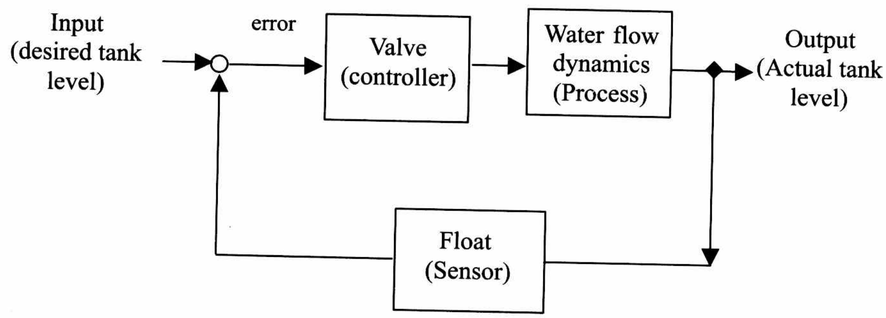

Fig. 1.5 Block diagram of closed loop system

Thus for more accurate and more adaptive control, a link or feedback must be provided from output to the input of a open-loop control system. So the controlled signal should be fed back and compared with the reference input, and an actuating signal proportional to the difference of input and output must be sent through the system to correct the error. Thus feedback is the property of a closed-loop system, which permits the output to be compared with the input to the system, so that the appropriate control-action may be formed as some function of the output and input. In general, feedback is said to exist in a system when a closed sequence of cause-and-effect relations exists between system variables. A closed-loop idle-speed control system is shown in Fig.1.6.

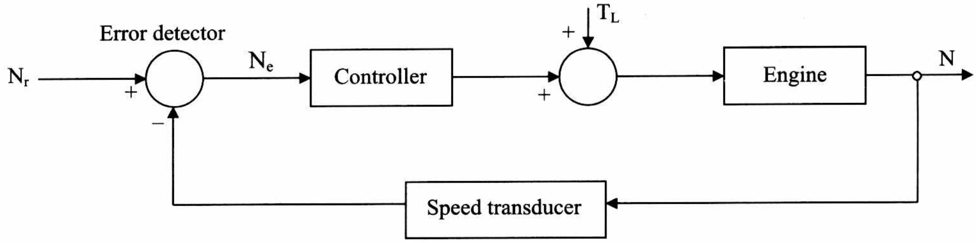

Fig. 1.6 Closed-loop idle-speed control system

The reference input N_r sets the desired idle-speed. The engine speed at idle should agree with the reference value N_r and any difference such as the load-torque T_L is sensed by the speed-transducer and the error detector. The controller will operate on the difference and provide a signal to adjust the throttle angle a to correct the error. In daily life, feedback control systems are formed in almost every aspect. In the home, a refrigerator utilizes a temperature control system. The desired temperature is set and a thermostat measures the actual temperature and the error. A compressor motor is utilized for power amplifications. Other applications of control in the home are the hot-water heater, electric iron, and oven, which work on similar principle. In automobiles also automatic controls are used for maintaining constant speed, constant temperature and engine control. Modern industrial plants utilize robots for obtaining temperature controls, speed controls, position controls etc. another field is chemical process control where a control engineer is interested in controlling temperature, pressure, humidity, thickness, volume, and quality etc.

Example 1.2: Draw a block-diagram representation of a thermostatically controlled electric oven in the kitchen of a home

Solution: The block diagram is shown in Fig. 1.7.

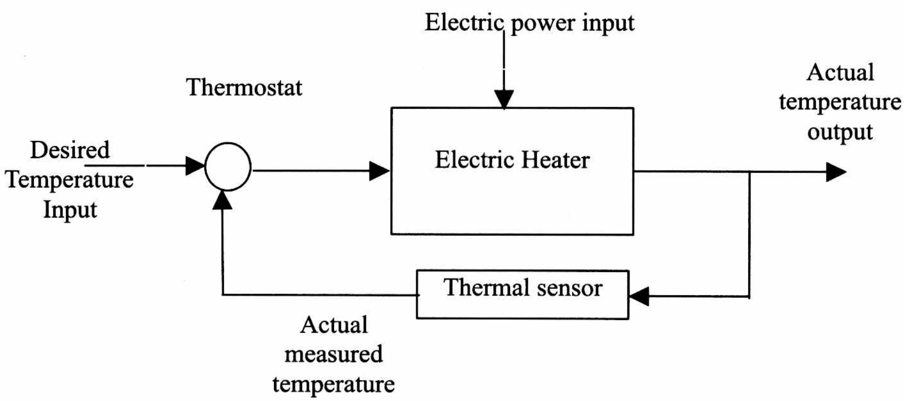

Fig. 1.7 Thermostatic controlled electric oven

Example 1.3: Devise a system that can control the position, rate and acceleration of an elevator used in an apartment house. What specifications or limits would you place on the position, velocity and acceleration capabilities of the system?

Solution: The basis system would require that the elevator's actuating signal be proportional to position, velocity and acceleration. Theoretically, this could be obtained by feeding back electrical signals proportional to position, velocity and acceleration and comparing them with reference signals. In practice, this can be simplified by placing integrators properly within the control system in order that only electrical signals proportional to position and perhaps velocity need to be sensed.

Specifications must be placed on the velocity and acceleration capabilities in order that they are limited to safe values from the passenger's view point.

Example 1.4: Identify the organ-system components and the input-output and describe the operation of the biological control system consisting of a human being reaching for an object

Solution: A simple block diagram describing the process is shown in Fig. 1.8.

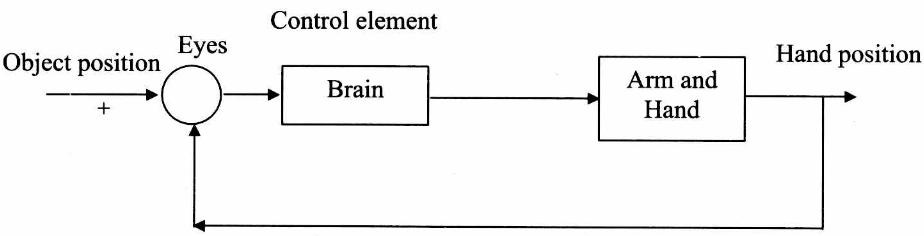

Fig. 1.8 Biological control system

The basic components of this intentionally oversimplified control system description are the brain, arm, hand and eyes.The brain sends the required nervous system signal to the arm and hand to reach for grasping the object. This signal is amplified in the muscles of the arm and hand, which serve as a power-actuator for the system. Eyes are employed as sensing device, continuously monitoring the hand position and sending the error to the brain. Hand position is the output for the system and the object position is the input. The objective of the control system is to reduce the distance between hand position and object position to zero value.

Example 1.5: Explain how the classical economic concept known as the law of supply and demand can be interpreted as a feedback control system. Choose the market price (selling price) of a particular item as the output of the system and assume the objective of the system is to maintain price stability. Draw the block-diagram.

Solution: Generally the market demand for the item decreases as its price increases. The market supply usually increases as its price increases. The law of supply and demand says that a stable market price is achieved if and only if the supply is equal to the demand. The following four basic elements for the system: the supplier, the demander, the pricer and the market (where the item is bought and sold) are chosen as the variables. The input to this idealized economic system is price stability. The output is the actual market price. The system operates as follows:

Figure 1.9 shows the block-diagram of this economic law of supply and demand.

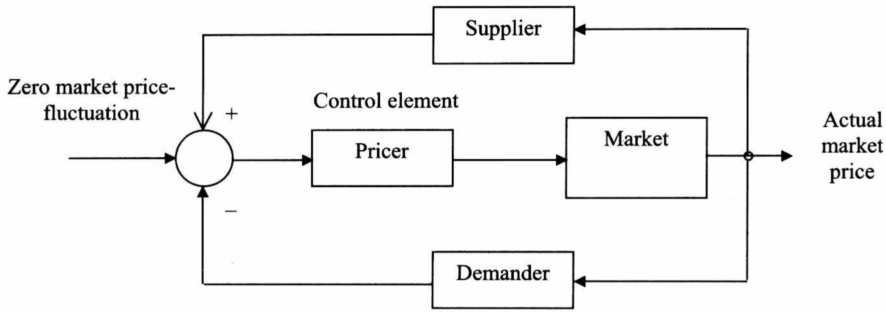

Fig. 1.9 Economic law

The pricer receives a command for price stability. It estimates a price for the Market transaction with the help of information from its memory. This price causes the supplier to produce or supply a certain number of items and the demander to demand a number of items. The difference between the supply and demand is the control action for this system. If the control action is non-zero, that is if the supply is not equal to the demand, the pricer initializes a change in the market price in a direction which makes the supply eventually equal to the demand. Hence both the supplier and the demander may be considered the feedback, since they determine the control action.

1.2 ANALYSIS OF FEEDBACK

Feedback is that characteristic of closed-up control system, which distinguishes them from open loop systems. It permits the output to be compared with the input of the system so that appropriate control action may be formed as some function of output and input.

The presence of feedback imparts to a system the following most important features:

(a) Increases accuracy, by reducing steady-state error in tracking a reference.

(b) Reduces sensitivity of the transfer function for the variations in system characteristics.

(c) Reduces the effects of non-linearities and distortion.

(d) Increases bandwidth, where bandwidth of a system is that range of frequencies (input) over which the system will respond satisfactorily.

(e) Stabilizes an unstable process.

Feedback requires a sensor and feedback systems are more difficult to design and operate than open loop systems. Feedback control systems may be classified in a number of ways, depending upon the purpose of classification. For instance, according to the method of analysis and design, control-systems are classified as linear or non-linear, time-varying or time-variant systems. According to the types of signals used in the system, they may be: continuous data and discrete-data system or modulated and unmodulated systems. In describing the mathematics of feedback, the term *gain* is often used. Gain refers to input-output description of the behavior of a system and is nothing to do with the internal structure of the system or its behavior. In mathematical sense it is called *transfer function* of the system. Consider the simple feedback configuration shown in Fig. 1.10.