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Computer-Based Industrial Control

Krishna Kant

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COMPUTER-BASED INDUSTRIAL CONTROL
by Krishna Kant

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Foreword

The history of control can be traced back to the history of mankind. Since the beginning, man had been devising artifacts to sense various parameters and to control them. While recorded history of technology development can be considered in terms of thousands of years, the serious study of technology and its development has occurred only during the last 100 years. The two World Wars have been responsible for the rapid development of automation technology. Undoubtedly, the advancements in micro-electronics technology and emergence of microprocessor have triggered a boom in these developments.

The process control area can be divided into three streams, namely, the Techniques, the Components, Subsystem and System Architecture. These streams though developing independently are converging each other. The process control techniques involve the classical controls and its developments. The last few decades have seen the consolidation of classical controls as well as a shift towards Model Based Adaptive as well as Self-Tuning Control. These techniques are being used increasingly in industries. The latest developments are in the field of intelligent control using expert systems, fuzzy logic controller and neurocontrollers.

The field of *components* has seen a number of developments in the form of specialised Microprocessors (Microcontrollers) which can be used for process control directly. The sensors and actuators, the two major components in process control have developed enormously in the form of Silicon Sensors, Fibre-Optic Sensors, Biosensors, Electronically Actuated Valves, Digital Valves etc. The field of subsystems has seen the developments in the form of SCADA systems, Remote Terminal Units for Telemetry and Telecontrol, Programmable Controllers, Distributed Digital Controllers, Personal Computers etc. The software systems supporting the process control have developed into Real-time Operating Systems and Real-time Programming Languages.

The *architecture* developed for process control over the years includes Distributed Digital Control, Distributed SCADA Systems, Multi Microprocessor Architecture using Local Area Network Concepts, Telemetry and Telecontrol Systems using Remote Terminal Units etc.

These streams have been successfully implemented in a number of applications in industries. The present book covers all the streams and the developments in detail, including the case studies of automation in some of the major industries. The exposure to these developments is more often not provided to undergraduate as well as postgraduate students in colleges and universities. The book is, therefore, useful for students offering courses on instrumentation, process control, automation etc. at both the levels.

I know Dr. Krishna Kant since 1979, when he joined the Department of Electronics as a Senior Systems Engineer in Appropriate Automation Promotion Laboratory. During these years, he has been deeply involved in the development of number of automation projects and subsystems. The book is therefore a result of his experience and learning of this field. The presentation of the subject in the book is simple and gradual. This book is a must for all practising instrumentation engineers in the field.

Dr. N. Seshagiri,
Special Secretary, Planning Commission &
Director General (NIC)

Preface

Today, the study of process control systems or automation in various engineering institutes and universities is confined to the theoretical aspects, which can hardly be applied to the real-world problems. This book, which is an outgrowth of my teaching experience in Delhi University as well as my practical experience, is intended to give a practical thrust to the subject. For, I found during the course of delivering my lectures, that there is a dearth of books available that are useful to the students or the practising engineers when they are faced with practical problems. Hence the need for a book such as this.

The main objective of this profusely illustrated book is to impart a solid application-oriented knowledge of the technology spanning the Industrial Control field. This technology includes control instrumentation (i.e. sensors, controllers and actuators), computer hardware and software, data communication links and the relevant advanced control techniques. It also incorporates some specialised sub-systems like Programmable Controllers, SCADA systems, Remote Terminal Units, etc. The Distributed Digital Control is an important field which has come in a big way in all industrial control applications. Another area, though recently introduced and which has made great impact, is the application of Personal Computers as a low cost tool. These have become increasingly powerful, thanks to the advent of more and more powerful microprocessors. In this book, special emphasis is laid on the case studies on the application of various fields, like Distributed Digital Control, Programmable Controllers, SCADA, Remote Terminal Units. The knowledge gained through these case studies could be utilised in real-world problems.

The book *introduces* the subject of automation—its historical development, basic functions and current trends. Chapter 1 is devoted to the fundamentals of automatic process control and its various types. Chapter 2 discusses the transducers which sense the process and present the electrical signal to computer. Covering both present and futuristic transducers, it also includes a special section on Biosensors. Chapter 3 gives the user a detailed account of the building blocks of automation system, and various modules used in these automation systems. Direct digital control structure as well as the control algorithms have been discussed in Chapter 4. Programmable controllers, their programming languages like ladder diagram, Boolean mnemonics and functional blocks etc. have been covered in Chapter 5.

Distributed digital control is covered in Chapter 6. The four-level hierarchy of a typical distributed digital control has been discussed in detail, including the examples of some of the well-known distributed control systems. Chapter 7 presents a cursory glance of display systems and computer graphics and graphical user interfaces used in distributed control system. Chapter 8 discusses various types of actuators, control valves and interfacing of the control elements to computers and microprocessors. The intricacies of software which control various tasks and the real-time operating system have been presented in Chapter 9. The personal computer and its applications in real-time environment alongwith its interfacing to outside world are the topics of Chapter 10. This chapter also gives the present system design strategies followed by various manufacturers of modules which can be readily used with personal computer. The advanced control techniques using modeling and simulation have been briefly presented in Chapter 11.

Chapter 12 discusses the application of industrial control system in various industries in form of case studies. It gives in-depth analysis of process intricacies and evolves control strategies for these industries, viz. steel, cement and power, water treatment plant and irrigation canal.

Chapter 13 briefly describes intelligent controllers covering AI systems, expert controllers, fuzzy and neuro-controllers.

While writing this book, special care has been taken to make it *modular*, and thus each chapter can be viewed as a specific module. It has been assumed that the reader has the fundamental knowledge of process and has basic background of electronics, control instrumentation and microprocessors.

This book would be found useful by undergraduate and postgraduate students offering courses on control system design, instrumentation engineering and advanced control systems. These courses one offered in almost all the universities in India. The teachers will find this book very useful while planning their courses. As this book is more oriented towards applications rather than theory, the practising engineers should find this book highly useful.

Krishna Kant

Acknowledgements

A large number of persons have directly or indirectly contributed to this book. Its my pleasure to acknowledge my gratitude towards all.

The initial inspiration to transform my knowledge and experience into book form came from Dr. N. Seshagiri, Special Secretary, Planning Commission. My close friends like Dr. Vijay Bhatkar (Executive Director, CDAC), Prof. D. Popovic, University of Bremen and (Late) Shri G.S. Vardhan (Director, Software Technology Park, Bangalore) continued to inspire me throughout the period the book was written.

I have received encouragement and friendly suggestions from Shri S. Mukhopadhyay and Dr. Ashok Chakravarti (Advisers, Dept. of Electronics).

Students of the course on Real-time Control of Processes, participants of various training programmes of 'PC Based Systems Design' and large number of engineers from RDCIS, SAIL (Ranchi), various steel plants, IL(K), CMC, BHEL, Delhi Water Supply, Irrigation Department, (Govt. of Maharashtra), National Council for Cement and Building Materials, various IEPP centres and number of instrumentation industries, etc. have also helped me to crystallise my concepts.

Friends like Dr. (Mrs.) Hema Khurana and Shri Ravichandran have contributed by compiling various chapters and giving their valuable advise. Here, I wish to have a special mention of my other friends in Microprocessor Application Engineering Programme, New Delhi who have contributed in literature survey and compilation. Also, I would like to have a special mention of my secretarial staff, who painstakingly for the past five years carried on the job of data entry and made modifications number of times.

A large part of the book was written during my tours. I wish to acknowledge the excellent facilities of Indian Airlines which to my experience is the best domestic airline in the World and the airline which really cares for the comforts of its passengers.

The book would not have been completed without the love, understanding and patience of my wife Dr. (Mrs.) *Madhu Chhanda* and children *Prashant Rishi* and *Neha Shikha.*

Krishna Kant

0

Introduction

In our industrial society today, the information is the most strategic resource. It is, therefore, inevitable that the information technology sector will gain ground over manufacturing and goods producing sector. Creation, processing and distribution of information will therefore be the predominant economic activity of the future. The information technology sector will in general include tools for accomplishing the above task. The identifiable parts are computers, communication and industrial controls.

The nature of both data handling and processing task is changing. Computing is moving from a sequential, centralised world to parallel, decentralised world in which a large number of systems must work together, thus calling for a new generation of general purpose computers. Technologically and socially, the needs for future generation of computers are becoming increasingly demanding for example computer architecture (including distributed architectures supporting computer networks, viz., Local Area Networks (LAN), Wide Area Networks (WAN), and Parallel Architectures) which provide high speed computers for numerical calculations and VLSI architectures make full use of the potential of VLSI technology.

The VLSI technology is making very rapid strides which has enabled the industrial applications of computers to become more and more viable. The processing architectures, the memory technology and the man-machine systems which are important for processing and distribution of information in industries are undergoing metamorphic changes. The computing power is facing an exponential growth, while the cost per bit of information processing is rapidly falling. It is becoming clearly evident that the digital computer must form the basis for the industrial control system of the future.

As a result, one of the most important recent trends in the development of automatic controls in all industries has been to cover the whole plant under a unified coordination and control, and to begin automating the entire operational supervision system using a hierarchy of computer. Presently, systems are being designed using expert systems, neural networks, transputers and high performance microprocessor for dedicated applications. The multimedia based man-machine interface is topic of research being persued.

0.1 EXPECTATIONS FROM AUTOMATION

To control a complex process we must first understand the factors which influence the performance of the process. In industries, the quality of the input raw materials varies and so is the skill of the operator. Hence, the importance of process control becomes significant in order to produce materials of consistent quality at a competitive price.

The dependence on the skill of an individual operator was found to be inadequate, and hence, the use of process instruments came in. This was further extended when the concept of automation was introduced. An automatic control system could perform a repetitive job; but could not take any decision in the event of variable circumstances. Gradually, the important industries started using microprocessors and computers for real-time application in the process control. Here the control system monitors the status of the process continuously and takes corrective action dynamically to stabilise the process.

Complex process industries like steel, cement, power, etc. require both extensive closed loop controls, exhibiting a high degree of accuracy as well as sequence controls with complex logic functions.

An analysis of these requirements leads to the following demands on the control system concept:

— High reliability and availability

— Fast trouble shooting

— Simple operation

— Easily configurable

— High accuracy and reproducibility of process parameters and process variables

— Low cabling cost

— Availability of process computers for optimization functions and processing of operating data

— Flexibility as regards modifications and extensions required by the process.

0.2 BASIC FUNCTIONS

Automatic control of any modern industrial plant, whether achieved by a computer-based system or by conventional means, involves an extensive system for the automatic monitoring of a large number of the different variables, operating under a very wide range of process dynamics. It requires the development of a large number of functions, some of which might be quite complex, for the translation of the plant variable values into the required control correction commands. Finally, these control connections must be transmitted to another very large set of widely scattered actuation mechanisms of various types. Because of the nature of the manufacturing processes involved, these may, and often do, require the expenditure of very large amounts of material and energy. Also, plant personnel, both operating and management, must be aware of the current status of the plant and each of its processes.

In addition, such an industrial plant always faces the problem of adjustment of production schedule according to the customer's needs, as is the new order stream being continually received. This should be achieved while maintaining a high plant productivity and the lowest practical production costs. The problem is handled in most cases through manual, although computer-aided, production-control system along with an in-process and finished goods inventory as judged adequate by plant personnel.

It has also been repeatedly shown that one of the major benefits of the use of the digital computer control systems in industrial plants is its role of a "control systems enforcer". In this mode, the lower level computers main task is to continually assure that the control system equipment is actually carrying out the job that it was designed for, i.e. to keep the units of the plant production system operating at some optimal level, and to ensure that the controllers have not been set on manual, but that on the optimal set-points.

Often the task carried out by these control systems have been those which a skilled and attentive operator could readily have done. The difference lies only in the degree of the attentiveness which can be achieved over the long run.

As stated earlier, all these functions must be factored into the design and operation of the control system which will operate the plant, including the requirements for *maximum productivity* and *minimum energy* usage. As the overall energy and productivity based requirements, become more complex, the need of more and more sophisticated and capable control systems became inevitable. In order to attain needed complexity and sophistication the field must gravitate more and more towards digital computer-based systems.

0.3 HISTORICAL DEVELOPMENT OF CONTROL SYSTEMS

All the human beings are gifted with five senses to understand and explore nature. However, it was soon realised that these senses are not adequate to satisfy their curiosities and demands and thus they started augmenting them. In order to explore, measure and gain access to the unknown it became absolutely necessary to develop diagnostic instrumentation. Most of the early instruments provided measurements of simple parameters, viz., length, area, volume, weight, etc. It was in the fields of astronomy and navigation that the most significant and accurate instruments were invented. As time elapsed, precision instruments pertaining to various other fields also were developed.

Today, instrumentation is present in all spheres of life. It meets man's requirements in all fields ranging from house to agriculture, entertainment to space exploration, simple measurement to complex process industries etc.

With the rapid development in electronic industry, the philosophy of instrumentation and controls has totally changed. Now a days, the philosophy is based on System Structure. The System Structure depends heavily on the technologies developed in recent years by the computer and telecommunication industries.

Historically the developments in the field of control systems can be grouped in (Fig. 0.1) the following areas:

— Early Development

— Pioneering Period

— Direct Digital Control Period

— Micro-computer Period

0.3.1 Early Development

In the early phase of development, machines were used to substitute for human physical power and the manual supervision and control was a necessity. Later the equipments for flow and quantitative measurement were developed and used.

The pace gained momentum when *pneumatic process controllers* first became readily available in the 1930's. These were self-contained devices and main disadvantage was that the operator had to be mobile in order to supervise these and had difficulty in gaining an overall impression of plant operations when large number of controllers were in use.

Subsequently development of transmitters (1950) gave a standard signal (3–15 psi, 4–20 mA) which could be sent over long distances, and thus, allow controllers to be grouped together for supervision. This concept of centralised supervision was introduced in mid 1960's by which time

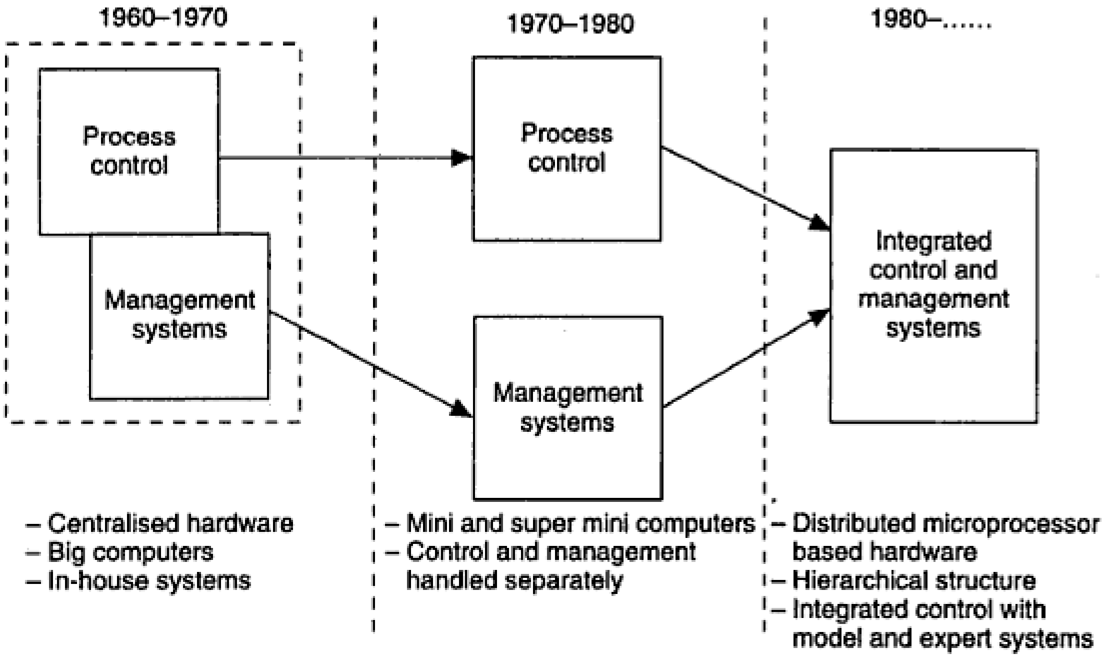

Fig. 0.1 Historical development.

Electronics Instrumentation was gaining popularity because of the availability of semiconductor devices.

During this period, PID (Proportional-Integral-Derivative) regulators became general substitute for automation problems as stand-alone control system. However, start-up and shut-down was through relays. The relays were also used extensively in sequence control system which along with the process control system often worked at cross purpose. However, the advantages and need of automation were established. The digital computers were first used in Monosanto Chemical Company Port, Arthur refineries in 1950. IBM 1700 was then used in oil companies.

0.3.2 Pioneering Period

The rapid development of electronic integrated circuits in the late 1960's was significant in two ways: *firstly* it prompted the design of the small and reliable analog electronic panel mounted instruments which have predominated in the last decade and *secondly* it led to the miniaturisation of digital electronics and the development of mini- and micro-computers.

The computers of this period were slow, expensive and unreliable and were therefore used in supervisory mode only. Two different approaches emerged for process control:

— Operator guide

— Set-point control

Major tasks performed by computer included production planning/scheduling, report generation on production, energy consumption etc. Control programs were hampered by lack of process knowledge and lack of good modelling methodology.

In early 1960's the major applications involved—control of steel mills, chemical plants, and electric power generation.

0.3.3 Direct Digital Control Period

With the introduction of computers, engineers felt the need of utilising computers advantages in instrumentation field through centralised control system. These advantages were optimisation, alarm and logging function, historic analysis, trending, sequence control and self diagnostic techniques. This gave birth to *Direct Digital Control* Philosophy in instrumentation with a back up of *Analog Control System.*

In 1962, ICI in England brought in a computer for Direct Digital Control which meant a computer controlling the process directly. The panel was simple; a digital display and a few buttons.

Special DDC languages were evolved for programming. User simply introduced inputs, outputs, regulator types, scale factors etc., while configuring system for their specific applications.

A number of specialised programs were developed in 1960's for DDC. Mini-computers made process control easier. Efficient process control systems based on DDC were designed. The number of process computers grew from about 5000 in 1970 to about 50,000 in 1975.

0.3.4 Microcomputer Period

Early 1970's gave birth to a new element in the family of Semiconductor Technology, namely MICROPROCESSOR. With the introduction of Microprocessor, Instrumentation Industries around the world, entered a new era due to the availability of the sophisticated control functions, high reliability, flexibility, speed, improved operational technique and the ease of the use in the applications covering various process requirements. The compatibility of Microprocessor to *Digital Data Communication* made it easy for system design engineers to connect widely separated system components over a *Data Communication Bus.* It is this ability to connect widely separated system components, which has led to the use of the term *Distributed System.*

0.4 CURRENT TRENDS IN COMPUTER CONTROL OF PROCESS PLANTS

The first total distributed control system was announced by Honeywell, USA(TDC2000). Since then, microcomputers have made their way into practically countless applications. Present day systems combine PLC functions, Data logging and Digital Control functions. New technologies, such as Artificial intelligence have emerged and new systems such as Expert Systems are increasingly becoming popular.

In recent years digital systems have become the mainstream of instrumentation and control technology. The digital systems have not only created a variety of advanced control systems, which considerably improved process controllability and product quality, but also is revolutionising the philosophy of control system as a whole. Recent developments in the field of microelectronics based on VLSI technology has given a new dimension to the electronics revolution. This new dimension is manifesting itself in the form of microcomputer based systems.

It is worthwhile, therefore, to briefly mention the current technology trend in the field of computer based instrumentation and control. The current trend in sensors and transducers is towards integrating *intelligence* into these along with the primary functions. The silicon integrated circuit technology has spread into this field as well. Semiconductor sensors are already popular for all applications, and the trend is to provide on-chip signal conversion and certain amount of intelligence for limit checking, etc. These are also reported to be directly compatible to be interfaced with control computers and other actuating elements. Fibre-optic technology has made possible the development of sensors which provide immunity against electromagnetic noise in the measurements. The Japanese iron and steel industry has already put them into practice and realised such benefits.

Programmable logic controllers are now designed around microprocessors. They facilitate the user to write programs in much easier and understandable language. New languages for programmable logic control are developed. The computer then generates the logic diagram on a CRT. PLCs are becoming available with powerful graphic facility to allow the user to change the relay logic diagram interactively. However, the conventional relay logic programming facility is also being provided for the user.

0.4.1 Centralised Computer Control System

The centralised computer concepts suffered many setbacks. In early years, of development, computers were slow, unreliable, memory sizes were limited and programming had to be done in machine language. Further, to help justify higher cost, vendors incorporated all types of computer, control functions including supervisory and DDC in one main frame at a central room located in the plant. As time elapsed, though computers became faster with bigger memory size and added features, the centralisation led to further problems such as the need for vast plant communication system. This was required to bring *process* signals to centralised computer system and return the *control* signals to the field. The probability of the failure of that one computer resulted in demand for a complete analogue back up system, paralleling the DDC. The complexity in programming the computers tended to increase and thus worsen the difficulties. A typical centralised computer control system is shown in Fig. 0.2.

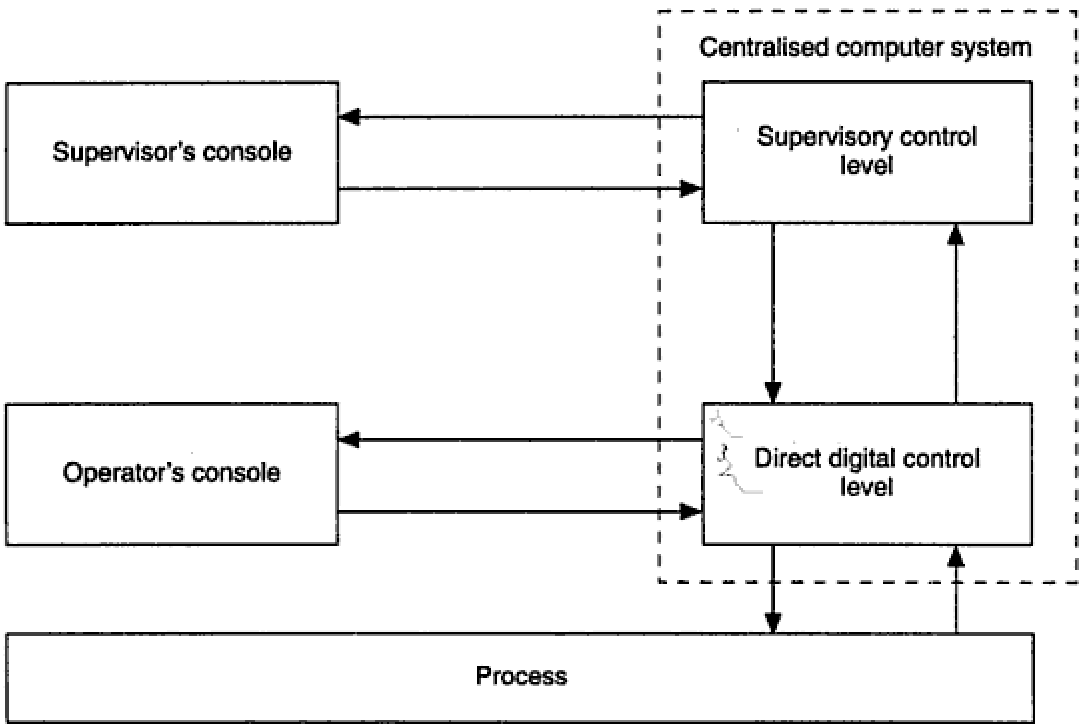

Fig. 0.2 Centralised computer system.

0.4.2 Distributed Control Systems

With the rapid advances in VLSI technology and the advent of single chip microcomputers with powerful processing capabilities which can be distributed physically, the distributed computer controls emerged. A distributed system is one which has several microcomputers which can be physically spread all over and each assigned with a specific task and all mutually linked through a data highway which can be coaxial or fibre-optic. Each of these microcomputers perform its own task concurrently and independently of the microcomputers in the system. Thus, this type of parallel processing provides excellent system response time and eliminates the possibility of any single-point failure crashing the whole system. The Honeywell Company, USA in 1969, took a courageous step to design an alternative to the centralised computer control system.

The 'TDC 2000' system as it was called, solved the problems of reliability by distributing the control functions to cover only few loops as well as providing a digital back up capability. This high reliability has greatly contributed to the success of distributed control. Several key factors such as increased reliability, elimination of disks to execute control algorithms, redundancy and extensive error-checking for communication highways, distributed display functions, redundant capability, back up control processors with automatic change-over are combined to achieve such a success. The MTBF for single-loop controllers seem to be atleast more than 20 years, though this figure may drop for multi-loop controllers. The advantage of distributed system however is the ability to upgrade (as the technology improves) without obsoleting the entire system.

Computer languages such as, Real-Time Fortran, Pascal and ADA have become most popular with distributed computer control systems. This is coupled with rapid strides in the developments in fibre-optics technology for wide-band communications between different computers in the system. Fibre-optic communication has enabled high data transmission rates of the order of gigabits/sec with a distance of about 2 km between two stations for reliable communication.

Man-machine interfaces such as powerful interactive colour graphics systems enable the user to generate/configure the various control loops, changing limits of any channel in any particular control loop 'on-line', and observe the performance of various control loops. The microprocessor based video terminals have made the task of human operators quite easy. Figure 0.3 shows a distributed digital control system.

0.4.3 Hierarchical Control Systems

The development of the distributed digital control systems greatly simplified the computer's connection to the process. Combination of the three levels of control (each with distinct duties), namely, the *dedicated digital controllers* for process loops, *direct digital control* for certain process variables and *supervisory control* levels, constitutes a hierarchical system. The upper computers depend upon the lower level devices for process data and the lower level systems in turn depend upon the higher level systems for even more sophisticated control functions such as an overall plant optimisation. Therefore, by combining company's production scheduling and management information functions with the process control functions, one can develop a total plant hierarchical computer control system as shown in Fig. 0.4.

It must however be remembered that all the elements in a hierarchical system can exist as individual elements. It should be noted that the different levels in a hierarchical system do not necessarily represent separate and distinct computer or hardware levels. One or more of these operational levels can be combined into one computer depending on the size of the system.

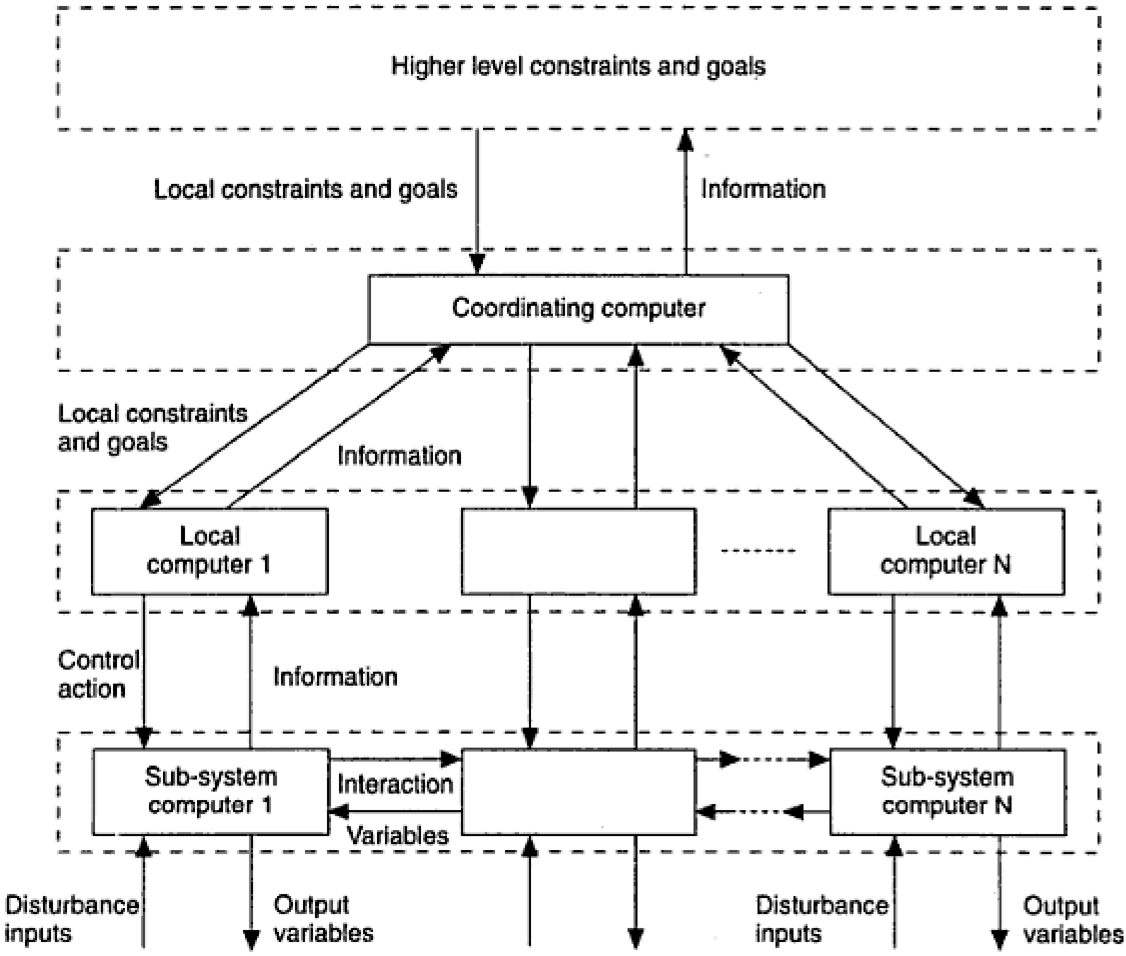

Fig. 0.3 Distributed digital control system.

0.4.4 Process Models

Modeling and simulation of systems has gained considerable importance during last three decades. This is due to rapid development of system and control theory during this time and especially due to rapid development of the computer technology. Generally speaking, no plant automation system can now be designed and put into work without using the methods of model building and simulation of the system to be automated.

0.4.5 Intelligent Control

In the recent past, many manufacturers of international stature have successfully made use of robotics to improve their production capability. A close corollary to robotics is Artificial Intelligence (AI). Although the problems of emulating human intelligence are staggering, one branch of AI-expert systems has reached the level of practical economic application.

Expert systems are computer systems which use knowledge and inference procedures developed from human expertise. The *knowledge* usually takes the form of computer rules coupled with observed facts. *Inference* is the logical process which combines rules and facts to produce new facts.

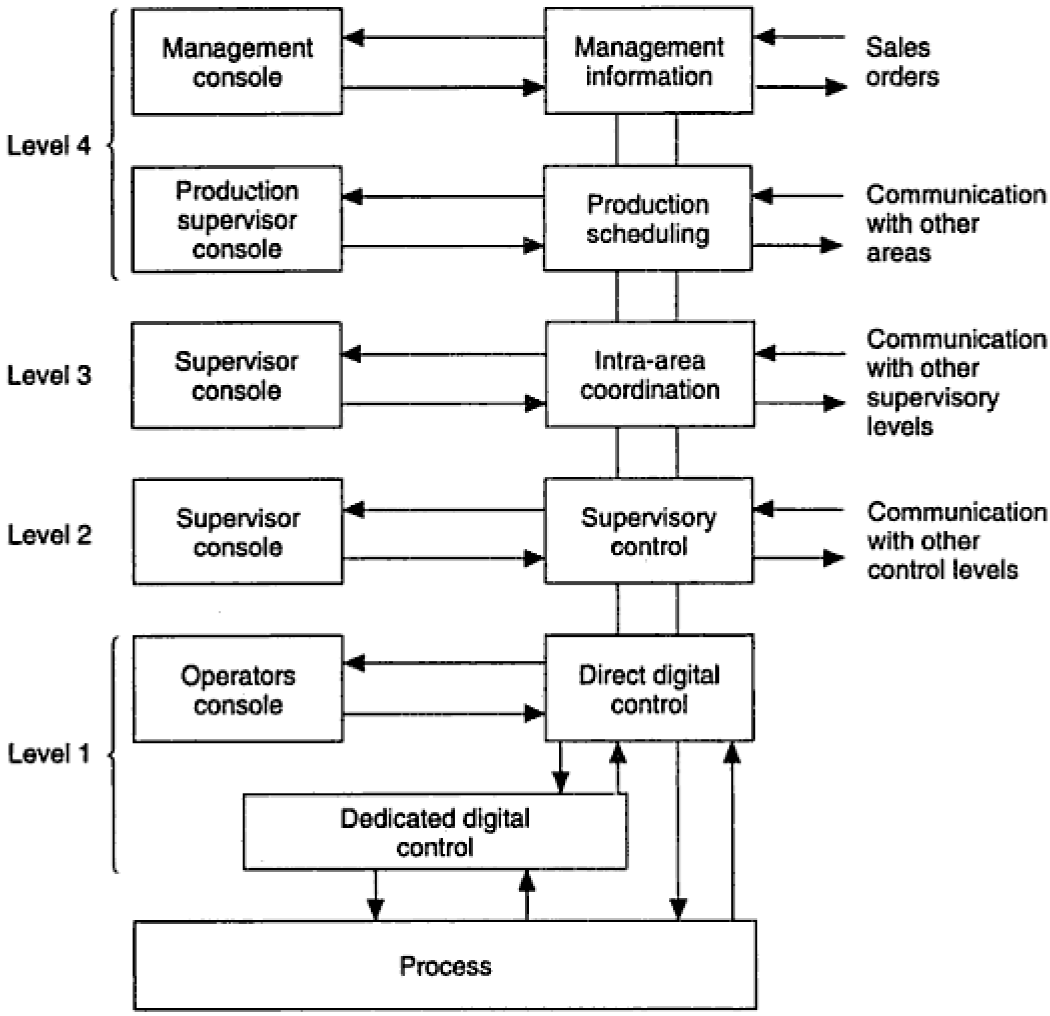

Fig. 0.4 Total plant hierarchical control system.

The two most widely used logic patterns in expert systems are the "Forward Chaining" and "Backward Chaining" patterns. Forward chaining systems accept input data and move through a rule base, thus deducing new facts. For instance, an input fact "a" will be incorporated into the rule "If a Then b" and the new fact "b" will be deduced and added to a list of other known facts. This logic pattern is useful in those applications where implications of each piece of new data must be evaluated.

Forward chaining systems are commonly called "production systems" because in each cycle they produce an additional fact. Rules in production systems are called "productions". AI researchers seem to favour this kind of system because it is a reasonable model of human thinking.

The "Backward Chaining" logic pattern, is "goal-oriented". The logic of this kind of system is accumulation of facts which will satisfy certain specific references of "goals". This logic is easier to computerise because the goals "inferred facts or conclusions" are already known and the system is concerned only with facts which will support a logical inference. This technique starts with a goal to be proven and works backwards to resolve it. Backward chaining expert systems direct user sessions by asking very specific questions. Facts unrelated to a current specific goal are not normally accepted.

If a narrow focus and lack of generality is accepted, the goal-directed approach can provide systems which operate efficiently, and are easy to write, easy to understand and provide excellent results in their area of expertise. The key components and interfaces of a typical backward chaining expert system are shown in Fig. 0.5.

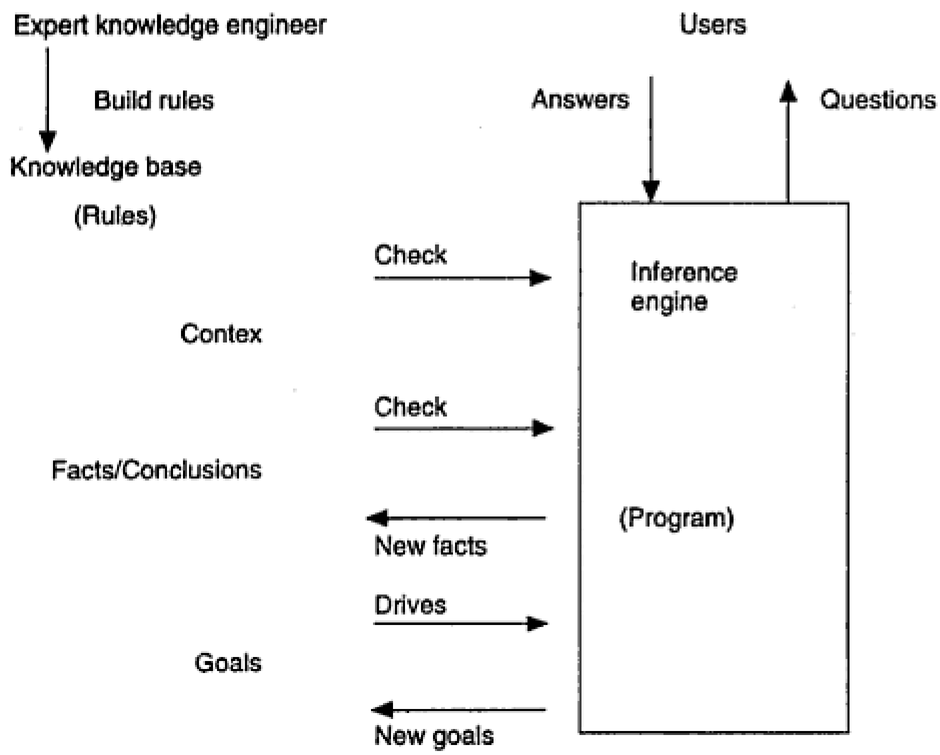

Fig. 0.5 Typical backward chaining expert system.

0.5 CONCLUSIONS

The field of automation and control is pretty vast and deep. We have introduced the subject in this chapter. In subsequent chapters, we shall be discussing some of the important topics in detail.

Process control and other industrial applications of computers have always been a relatively small fraction (approximately about 10 per cent) of the computer field, and thus it is a beneficiary but not a driver of this technology. Process control indeed had an input into the requirement of computer systems (necessary speeds, word lengths, memory size, reliability, allowable cost, etc.) but as a second order effect; process control has influenced the characteristics of the systems (which would have been built anyway) but probably did not generate their production in the first place. However, since it is believed that the needs of the process control field are not that much different from other applications, the general acceptable standards in the design of the computer systems should not be detrimental to the needs of the industrial computer systems.

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1

Fundamentals of Automatic Process Control

1.1 INTRODUCTION

To understand the process control techniques there are two major approaches. The first is the mathematics approach, where we make use of Laplace transforms, Z-transforms, control equations, stability criteria, system functions, Bode plots, etc. This approach definitely helps us to look into various intricacies of control system theory. A good number of books are devoted to this subject. According to the other approach the automatic process control is considered on a conceptual plane, i.e. as viewed by a system engineer. This implies that the systems intricacies are understood and different control actions are seen from the application point of view. The emphasis here is not to advocate a particular type of approach or to point out the pitfalls of one approach over the other, but to present the different facets of automatic process control on the conceptual plane.

1.2 PROCESS DEFINITION

The fundamental requirement for a process control engineer will be to define the process rightly. The process itself may be defined in a number of ways either as a set of different sub-processes and activities between them or by just describing input/output relation or going through each and every basic component and describing its composition. However, for the purpose of process control, process is defined in terms of various components and characteristics of the process required for control process.

Figure 1.1 shows an example of water heating system. The water is input at the bottom and the steam enters at "steam in". The hot water comes out at "water out" and steam at "steam out". In this particular example, the parameter we wish to control is the temperature of water. This is known as *control variable.* This can be controlled by varying the flow of steam. Thus, the steam flow will be known as *manipulated variable* or *controlled variable.* The other variables which we are not considering in this experiment are temperature of water input, ambient temperature in the atmosphere, etc. The variation in these parameters (variables) affects the controller and these are known as *load variables.*

Thus an automatic controller can be defined as, "Mechanism that measures the value of control variable and manipulates the manipulated variable or controlled variable to limit the deviation of control variable from the limit set."

This limit is known as set-point. The control of water heating system is shown in Fig. 1.2.

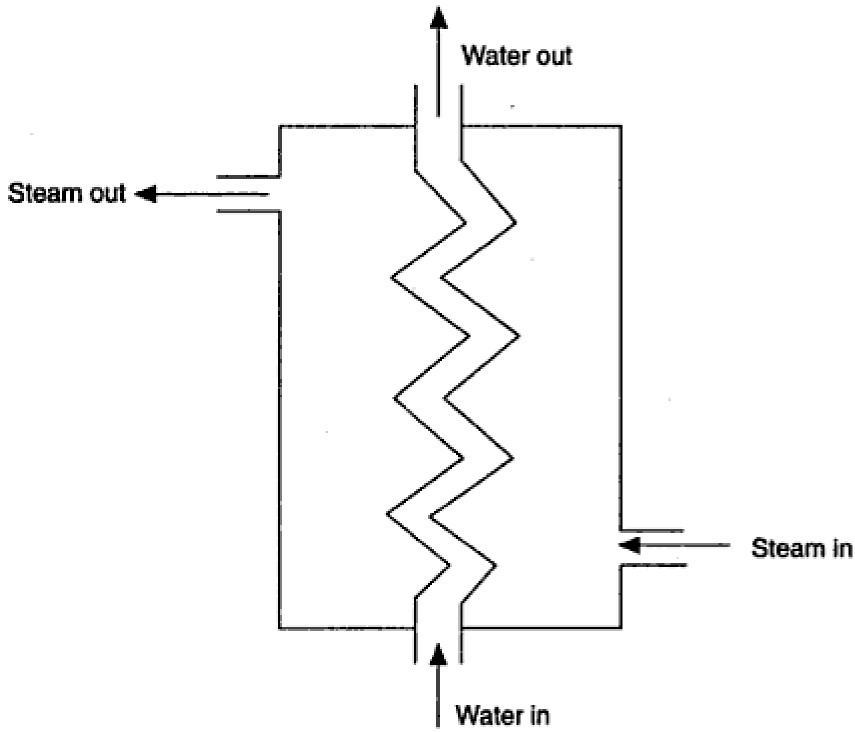

Fig. 1.1 Water heating system.

We have not yet defined the basic characteristics of the process which affect the control. Processes have characteristics of delaying or retarding changes in the values of process variables and which increases the difficulty of control. This is known as *process time lag*. The three characteristics of process which are responsible for time lags are: Capacitance, Resistance and Dead time.

The *capacitance* of the process is its ability to store energy or material. The *resistance* of the process is its basic capability to resist the transfer of energy. In the experiment shown in Fig. 1.1, the walls of the tank and also the coil having the water will be storing the energy and thus can be termed as the capacity of the process. Similarly, the steam layers around the coil will have insulating effect and will resist the transfer of heat from steam to water. This insulating effect will act as resistance of the process. Every process takes a finite amount of time to transfer the disturbance to the point of measurement like in our example shown in Fig. 1.2. If however the temperature of input water drops suddenly, then it will take some time to detect its effect at the output, as water will take finite amount of time to reach the point of measurement. During this time, no change takes place in the temperature of output water. This delay is known as *Transportation Lag* or *Dead Time* and is typical of the process. It is clear that dead time or transportation lag will depend on the placement of measurement point, velocity of disturbance, total distance etc. It is very difficult to measure the capacity and the resistance of any process. However, there can be a good estimate of the total process time lags.

1.3 FEEDBACK CONTROL

Feedback control system is that in which the control action is dependent upon the system output. A Close Loop System measures the actual system output, compares it with expected value and

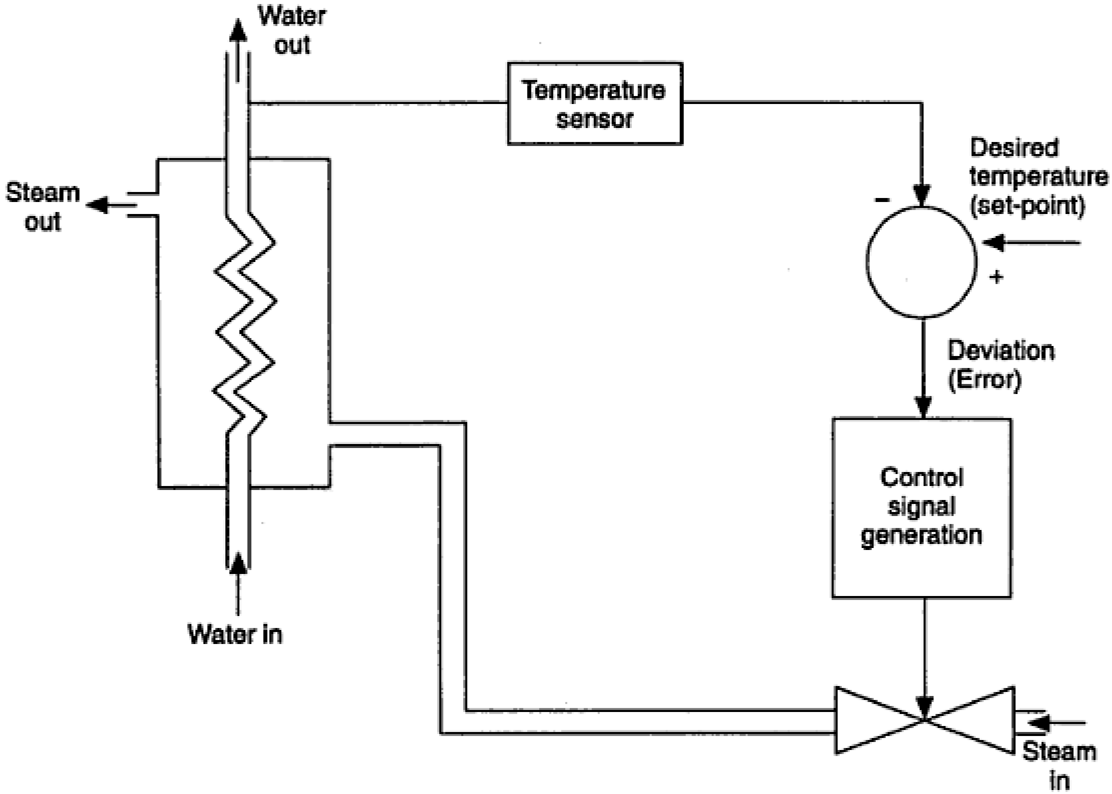

Fig. 1.2 Control of water heating system.

determines the error. This error value is then used to control the system output in order to obtain the desired output (Fig. 1.2).

1.4 BASIC PRINCIPLES OF A SINGLE CONTROLLER LOOP

Figure 1.3 shows the basic principle of a simple control loop. The level to be controlled is monitored by a level-sensing system with incorporated amplifier, the total being called *Transmitter.* The level transmitter LT sends a signal (4 to 20 mA or 0.2 to 1 bar) proportional with the level in the tank to the controller level LC.

The controller is the intelligent part of the loop and has three basic elements:

1. A *memory* for the desired level in the tank, Set-point (S)

2. A *comparator* for Set-point versus Measured Value, as reported by the Transmitter, producing the difference between these two, called the Control Deviation (error)

3. An *amplifier* amplifies the control deviation and produces the output of the controller.

The control valve receives the output from the controller and subsequently controls the input of the process.

It should be stated clearly here, that for a controller the input of the process is always the control valve or its equivalent. Through this element the controller can influence the process and consequently sense the results on the transmitter, the last one thus becoming the output of the process.

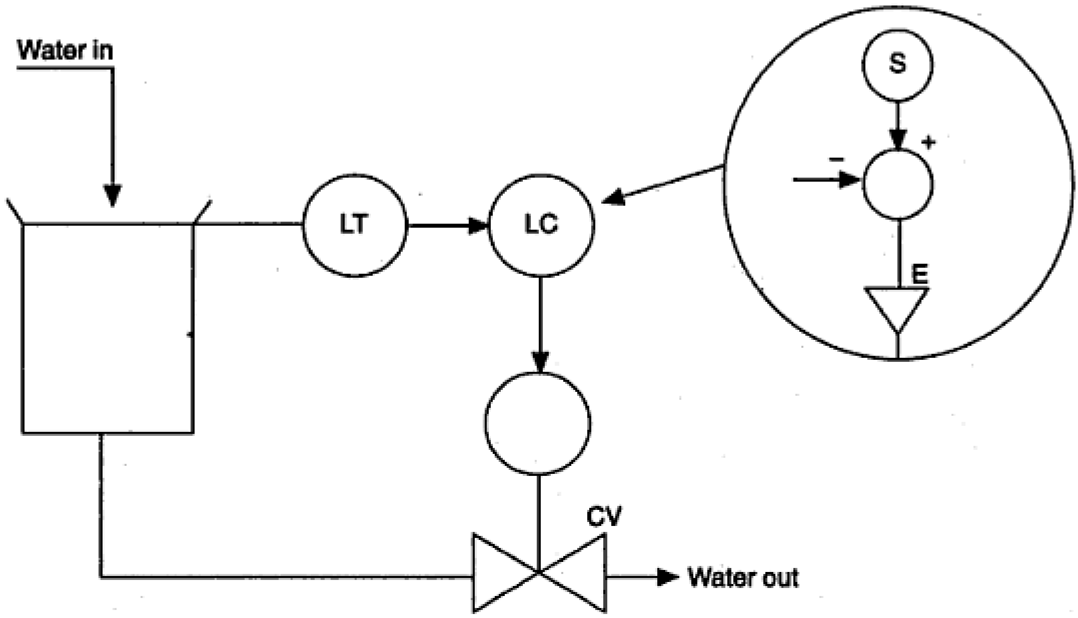

Fig. 1.3 Level control.

In the example in Fig. 1.4 it can be seen, that for control circuit the so-called information flow goes upward in the process from the control valve to the transmitter, while the material flow clearly goes downward in this application.

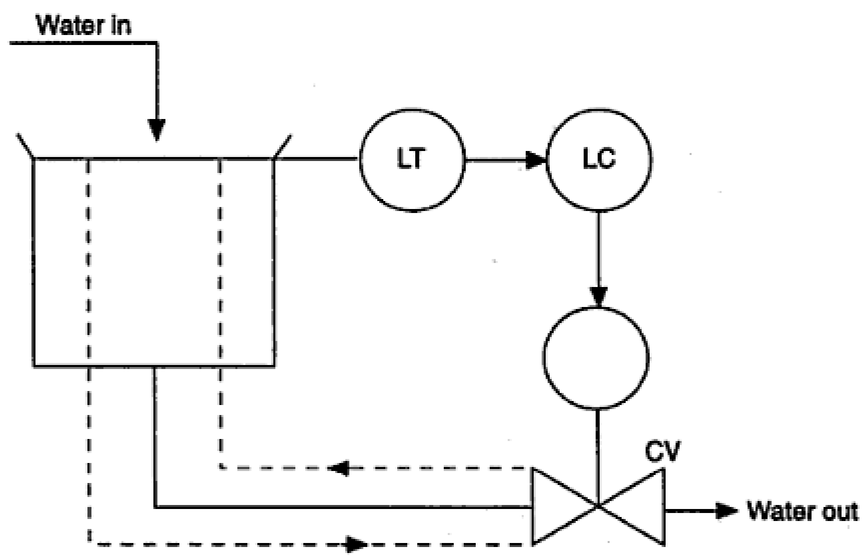

Fig. 1.4 Information flow in level control.

All the processes should be considered as having three serial subsystems in the following sequence:

1. A device, able to influence the input of the process, very often a control valve, in other cases for instance a speed controllable motor. These devices are mostly commanded by receiving a standard size signal of 4 to 20 mA.

2. The actual process, for instance in Fig. 1.3 with the outgoing flow as input and the level as output. The behaviour of this process can be seen as the effect of a change in control valve position upon the level in the tank.

3. A device, that measures the output of the actual process and translates this value back into a 4 to 20 mA range, thus making the information understandable for the controller. The device is also called sensor, transducer or transmitter.

It is very important to follow the above method of interpreting processes to be controlled, for the understanding of the dynamic behaviour of these processes. The controller 'sees' the whole process in totality and sends a signal 4 to 20 mA (control signal) and who reports back with some kind of signal (through transducer).

Next the task of the controller in a control loop is basically very simple. Since the difference between the measured value (MV) of the level and the desired value thereof (SP) is calculated, the controller should reduce this control deviation (error) to nil. Therefore, if the control deviation is zero, apparently the control valve is in the right position.

If the level is lower than the desired value, the control deviation will be positive and the controller output will be higher, thus forcing the control valve to open up further.

The basic question for the controller however is what should be the ratio between the control deviation and the variation in the position of the control valve? Various types of controls are enumerated here.

1. Two-position control
2. Multi-position control
3. PID control
4. Ratio control
5. Cascade control

1.5 TWO-POSITION CONTROL

Two-position control is simplest and cheapest form of automatic control used in process control. This is used when the control variables need not be maintained at precise values. Typical examples are controls of alarm or shut down functions.

In this mode of control, the final control element is moved quickly, from one of the two fixed positions to an other depending upon whether the control variable is greater than the set value or not. If these two are fully open and fully close positions then it is termed on-off control (Fig. 1.5).

A variation of the simple two-position control action is the two-position control with a differential gap in which a low set-point and a high set-point are defined. Figure 1.6 shows its characteristics. The valve is closed as the control variable crosses the high set value and shall remain closed till it crosses the low set value, then the valve is opened again.

This type of control is often used in industries where large capacities are involved and energy inflows or outflows are small compared to the system capacity.

1.6 MULTI-POSITION CONTROL

In this control, the final control element is moved to one of three or more fixed positions, each

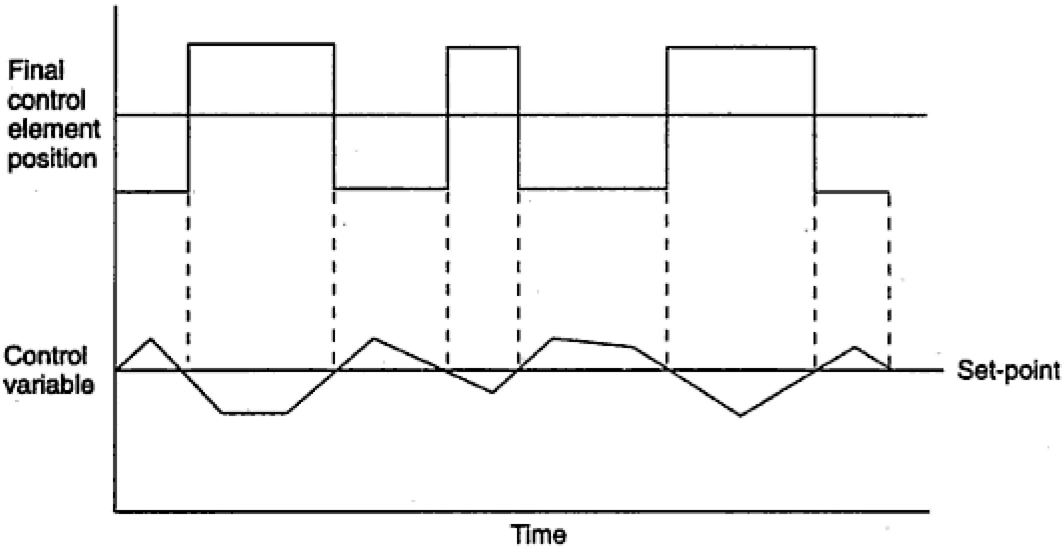

Fig. 1.5 Two-position control.

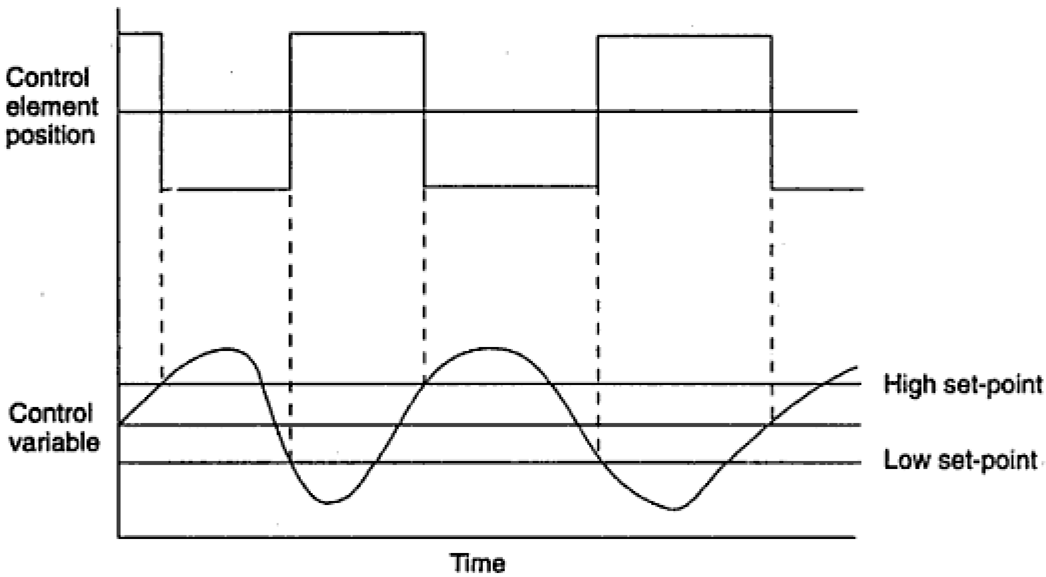

Fig. 1.6 Two-position control with differential gap.

corresponding to a definite range of values of the controlled variable, as shown in Fig. 1.7. In this control, the valve is closed when the control variable is above the high set value. When it is in the mid-band (i.e., between the high and low set values) the valve is half open and when it is lower than the low set value—the valve is fully open.

The drawback of both two-position and Multi-position controls is that, they rarely produce exact correction. The control variable continues to cycle around the set-point with considerable deviation on either side of the set-point due to the large capacitance and dead time involved, even when all the associated variables are constant.

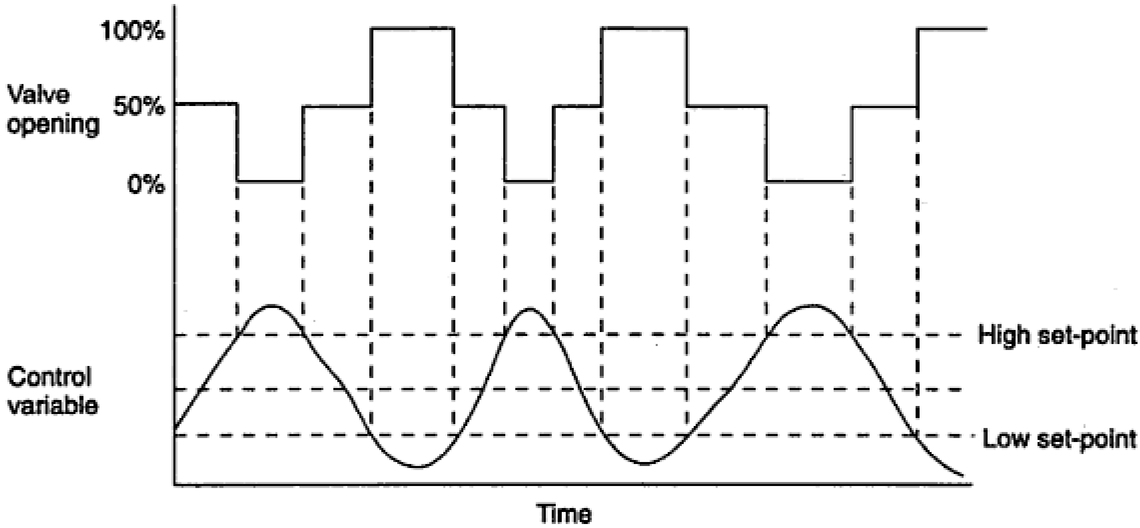

Fig. 1.7 Multi-position control.

1.7 PID CONTROL

PID control means Proportional, Integral or Derivative control, meaning that the control signal may be proportional, derivative, or an integral of error value. These three types may be used separately or in coordination.

1.7.1 Proportional Control

In the systems with proportional control there is continuous linear relation between the value of the control variable and the correction applied. The applied correction is changed by the same amount for each unit of deviation (Fig. 1.8).

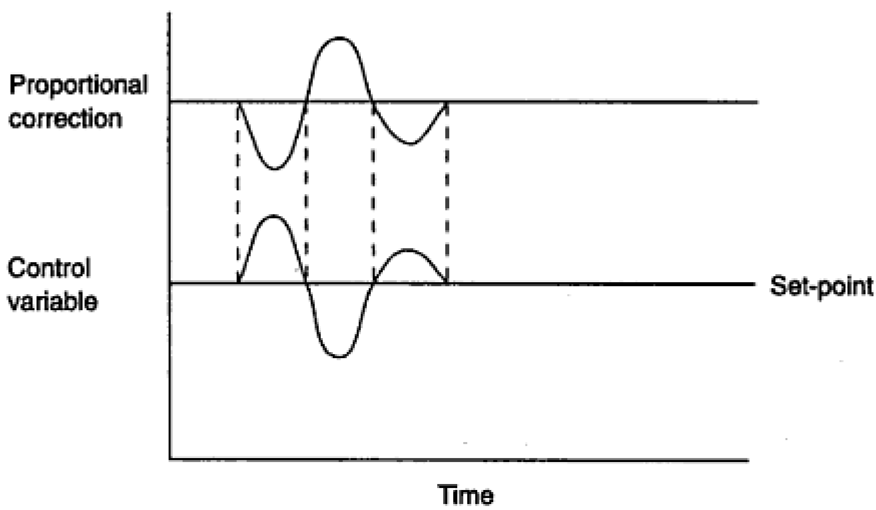

Fig. 1.8 Proportional control.

Following equation describes the input-output relationships.

$$Q_i = \frac{100}{PB}e + Q_0$$

where

Q_i = output at any given time,
Q_0 = output when $e = 0$, i.e. zero error,
e = error signal, i.e. set-point value – measured value,
PB = proportional band in percentage

Proportional band (*PB*) is defined as percentage of full-scale change in input required to change the output from 0–100%.

The proportional gain is defined as

$$\text{Gain} = \frac{\text{Proportional band}}{100}$$

In proportional controllers when the control variable deviates from the set value due to momentary disturbance, the controller gives a correction which is proportional to deviation. The correction forces the controlled variable towards the set value reducing the error which in turn causes a reduction in corrective action. Due to any load variation if the disturbance persists then corrective action given by proportional control will be insufficient to force the error to zero. This results in a residual error called 'proportional offset'.

For most processes the proportional controller has a disadvantage. To achieve a variation of the position of the control valve, it needs a control deviation. Hence in the example of Fig. 1.3 when the incoming flow is higher than normal, logic dictates, that to maintain the right level the outgoing flow must be higher and consequently, the control valve must be partially opened. The proportional controller will only do so, if at its input a control deviation exists and if because of a continuous higher inflow a continuous variation of the control valve position is needed, consequently a continuous control deviation will exist. As this continuous control deviation is due to the fact, that the controller has a proportional algorithm, this effect is known as *proportional control deviation* or *proportional offset.*

This finally leads to the fact, that the actual level in the tank is not the same as desired. To achieve the desired level, the set-point on the controller would have reset to a slightly lower value. This manual action to compensate the proportional offset in called manual reset (Fig. 1.9). Thus the limitation of proportional control alone is that it is not suitable for taking care of load variations.

1.7.2 Integral Control

The integral control signal is proportional to the error signal integrated over a period of time. Integral action continues to build up a correction till the error is forced to zero. The integral control overcomes the drawback of the offset error present in proportional control as the control responds to both magnitude of error and duration of error (Fig. 1.10). The correction given by integral action is given by

$$I = \frac{1}{KI}e \cdot dt$$

where

I = integral control signal,
KI = integral constant,
e = error at any instant 't'.

The limitation of integral control is that it is slow action as correction builds up gradually.

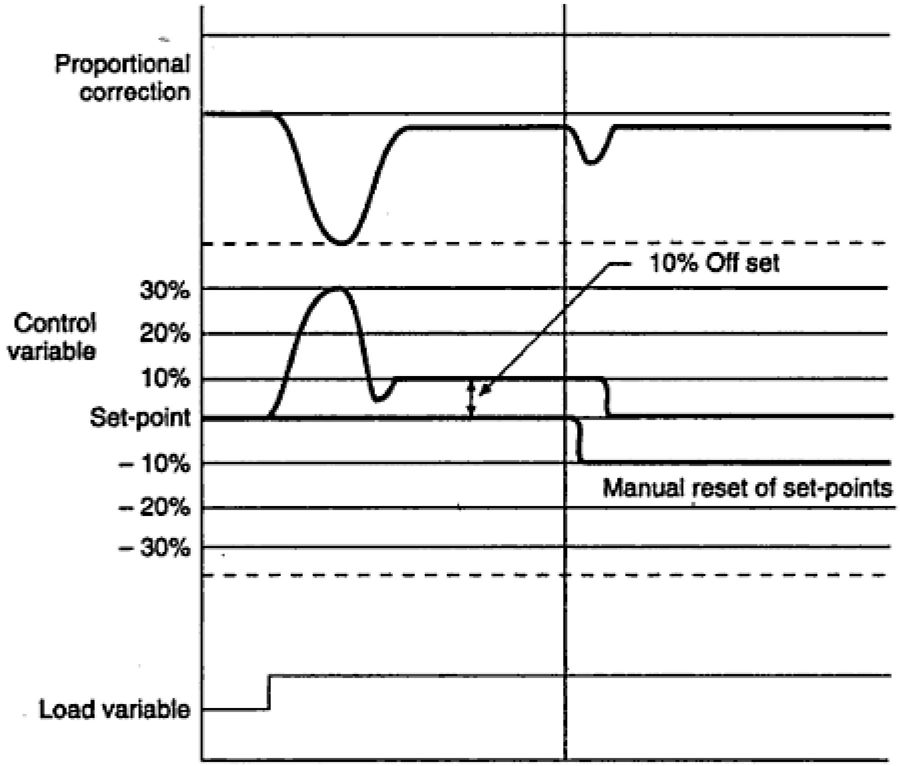

Fig. 1.9 Offset in proportional control.

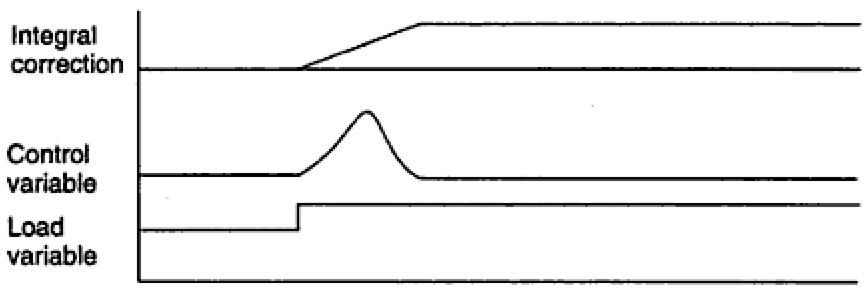

Fig. 1.10 Integral control.

1.7.3 Derivative Control

In this control, the correction is proportional to the rate of change of error. As soon as there is deviation, the derivative controls generates a momentary excess correction which speeds up the corrective action (see Fig. 1.11).

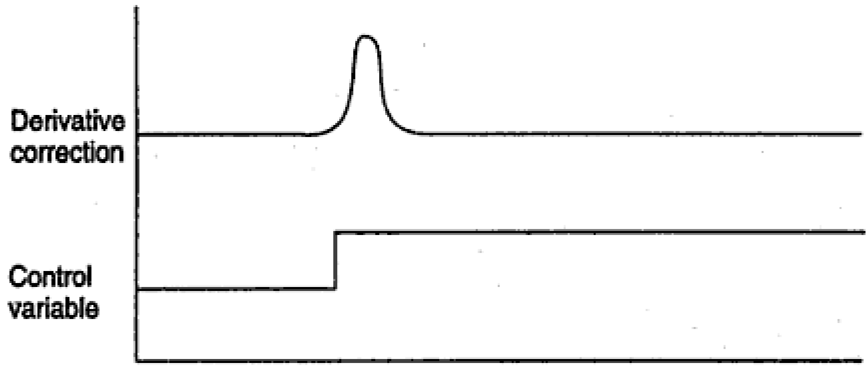

Fig. 1.11 Derivative control.

The correction given by derivative control is,

$$D = KD \frac{de}{dt}$$

where

D = derivative control signal,
KD = derivative constant,
e = error signal at any instant 't'.

1.7.4 Proportional Plus Integral Control

This controller not only varies the position of the control valve proportional to the offset, but also keeps enlarging this variation of the control valve position with the time.

This integral action of the controller continues with the time, until the offset has completely vanished. Therefore, the integral action of the PI-controller is also called the automatic reset.

The correction given by PI-controller is,

$$\text{PI} = \frac{100}{PB}e + Q_0 + \frac{1}{KI}e\,dt$$

The controller with the PI-algorithm enables the control loop to bring back the Measured Value (MV) to the set-point value. The time needed to achieve the required results, depends on the tuning of the controller. A PI-controller has two parameters to be tuned.

(a) The Proportional Band (PB) and

(b) The Integration Time (τ) or automatic reset time.

If a controller is tuned at 100 per cent an offset of 1 per cent will give a controller output variation of 1 per cent. However, if the controller is tuned at 25 per cent, the same offset will give an output variation of 4 per cent. Logic results in an output variation of 0.25 per cent for 1 per cent offset at 400 per cent PB setting.

The integration time is the time, the controller needs to drag the output for an equal variation, as initially done by the proportional action of the controller. If a controller is tuned at 50 per cent PB and Integration Time 20 seconds, then an offset of 2 per cent, appearing suddenly would result in a sudden variation of the control valve position with 4 per cent and a continuous rising of this 4 per cent to 8 per cent in the next 20 seconds and further to 12 per cent in the next 20 second and so on.

Evidently, in a normal operating control loop then the process output would also change and the offset would diminish and finally disappear.

The tuning of a controller is a delicate matter, since too strong actions of a controller give instability. In such a case the output of the process will continuously vary between upper and lower limits, the span between these limits being larger as the controller actions are stronger.

It is not easy to state definite rules for the tuning of the controllers without going into intensive theoretical details. As to the tuning of proportional and integral actions however, the following rules can be stated:

(i) *Lower proportional band.* Stronger proportional action will give faster reduction of offset, and therefore, tends to instability.

(ii) *Shorter integration time.* Stronger integral action will give faster reductions of offset and tends to instability.

1.7.5 Proportional Plus Integral Plus Derivative Control (PID)

The algorithm used for more demanding tasks is the PID controller with proportional, Integral and Derivative action.

The correction given is represented by,

$$\text{PID} = \frac{100}{PB}e + Q_0 + \frac{1}{KI}e\,dt + KD\frac{de}{dt}$$

where PB, KI and KD have the usual meaning, as explained earlier.

PID controllers are used where the derivative action can help to compensate for lags in the process. For example, in temperature control loops, the adverse effect of lag associated in the temperature-measuring element can be partially reduced by derivative control action. The controller senses the rate of movement away from the set-point and starts moving the control valve earlier than only with proportional or proportional integral action.

The derivative action can be best understood referring back to the control loop of Fig. 1.3 and presuming, that this loop is initially in a stable condition, which means, that the controller maintains a certain level on the set-point value. Now next the set-point is brought to a higher value.

While an intelligent operator would have to handle the control valve, he would open this quite forcefully and consequently a quick rise level is seen. On the arrival or near arrival of the level on set-point value, the position of the control valve is reduced back to the original position, thus ensuring a quick fill up of the volume, necessary to get the level on a higher value.

After that the operator would continue to control the level about in the same way, as a PI-controller would do, reaching on offsets with adequate proportional actions and subsequently with I-type dragging as a function of the time. Apparently the operator reacts in the beginning on the change of the offset, the speed and the size thereof.

The differential action acts exactly in the same manner on changes of the offset, and it gives additional controller output changes which are proportional to size and speed of change of the offset. The main problem with derivative action is that it amplifies any noise in the process signal, producing fluctuations in control valve position. Therefore derivative action is used only on signals that are free of noise (e.g. temperature). It is not recommended in flow control or level control loops.

It is very difficult to tune the differential action of a PID controller in the actual field. Therefore this algorithm is only used, when the normal PI-controller does not give satisfactory results.

It would be remarked however, that a well tuned derivative action gives faster control and tend to stabilize the control loop.

This mode of control employs the advantages of all the three modes:

1. *Derivative action* reduces the overshoot which often occurs when integral action is added to proportional action.

2. *Derivative action* counteracts the lag characteristics introduced by integral action.

3. *Integral action* reduces the offset when added to proportional control.

Figure 1.12 shows the behaviour of a typical feedback control system using different kinds of control, when it is subjected to permanent disturbance, like step change in load variable.

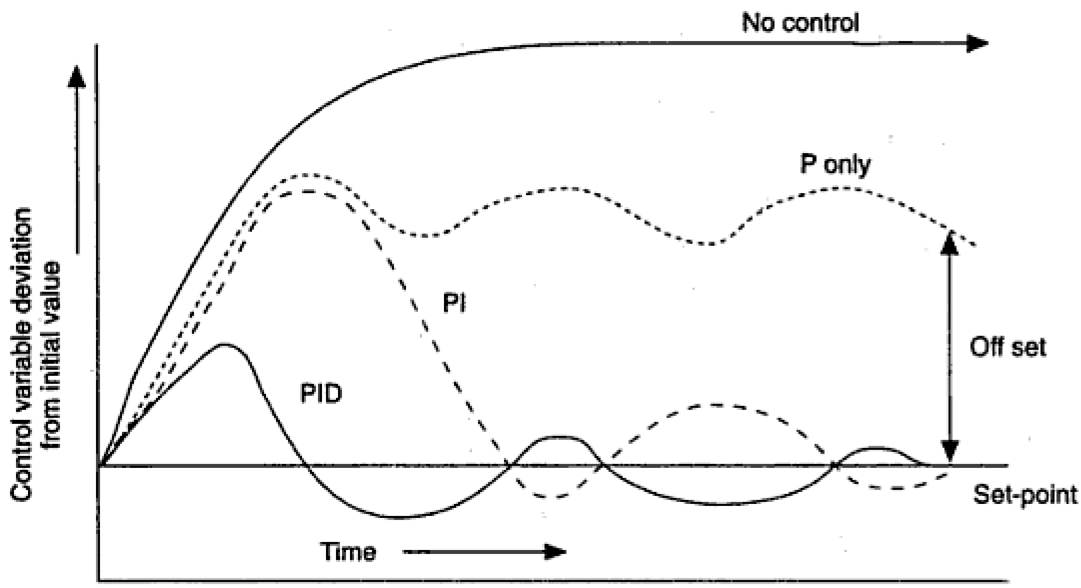

Fig. 1.12 Behaviour of different feedback control action (P, PI, PID).

1.8 MULTI-VARIABLE CONTROL

So far, we have discussed about feedback control loops with one manipulated or controlled variable and one measured or control variable. In real life, however, the control depends on many control variables, though there is only one controlled variable for each control loop. Such control loops are known as multi-variable control loops and more than one input signals jointly affect the action of the control system. Examples of multi-variable control are

— Cascade control,

— Ratio control.

1.8.1 Cascade Control

In many control schemes, the variation of some quality in the manipulated variable often degrades the control performance. In normal feedback, these changes have to enter the process, the effect is felt at the control variable and then only correction is possible. Where such changes are frequent, the system will be upset very often. Cascade control scheme gives a method to improve this discrepancy. Figure 1.13 shows the cascade control block diagram.

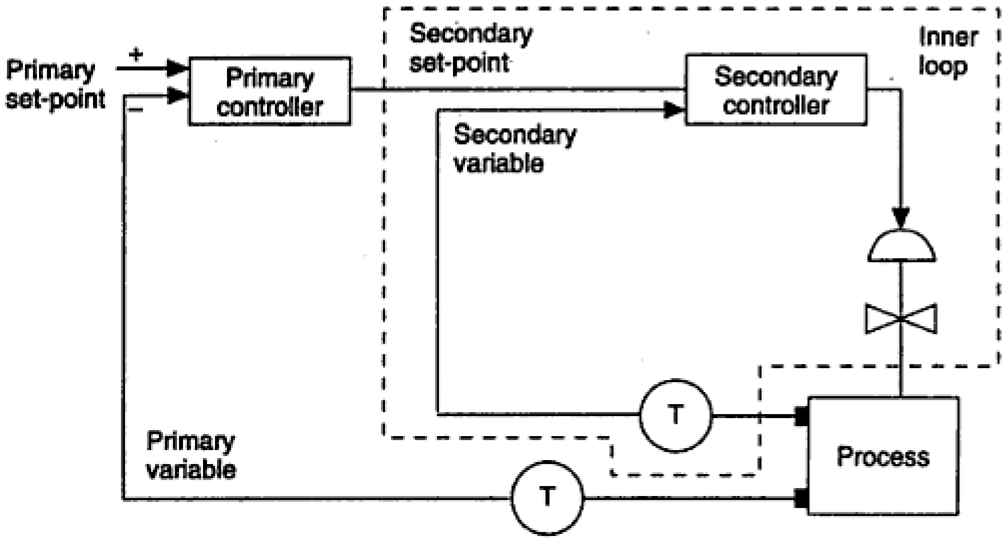

Fig. 1.13 Cascade control.

In cascade control, one controller manipulates the set-point of another. Each controller has a sensor but only master controller has a set-point while only the slave controller has an output to process.

The secondary controller, manipulated variable and sensor constitute the inner loop. The outer loop consists of all elements including the inner loop. The dynamics of the inner loop should be faster than that of the outer loop, e.g. flow through the inner loop and temperature through the outer loop.

The cascade control of water heating system is shown in Fig. 1.14. The Temperature Transmitter (TT) measures the temperature of water outlet and sends the signal to Temperature Control (TC), which compares the temperature of water outlet with desired temperature (primary set-point) and adjusts the set-point for steam flow (secondary set-point), for Flow Controller (FC). The Flow Controller receives the value of steam flow from Flow Transmitter (FT), compares it with the set-point fixed by Temperature Controller and sends the control signal to control valve to effect the flow control.

1.8.2 Ratio Control

In a ratio control system, a dependent variable (called secondary variable) is controlled as function of an independent variable (primary variable). The latter may be a free variable, i.e. measured but not controlled, or it may be automatically controlled. Although the ratio control is encountered most frequently in connection with control of flows, it is also used for other variables, like temperature, pressure, and composition. Typical system involving ratio control of two types of flow is shown in Fig. 1.15.

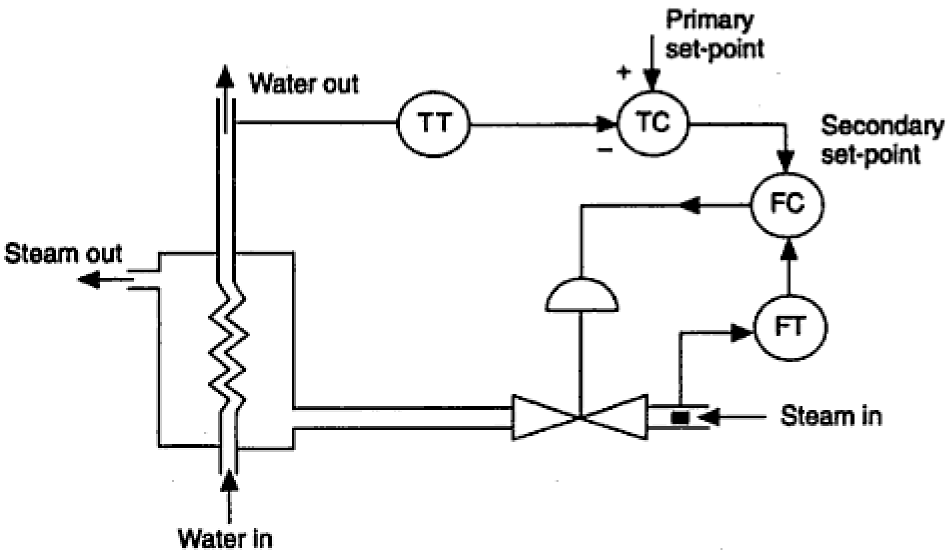

Fig. 1.14 Cascade control of water heating system.

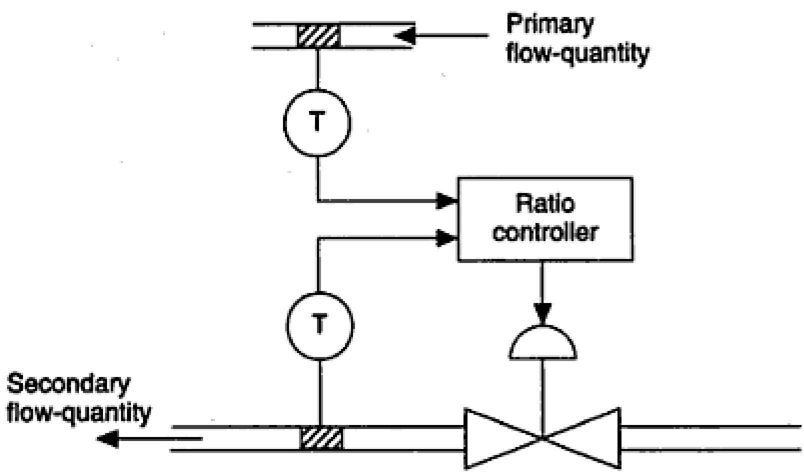

Fig. 1.15 Ratio control.

An example of ratio control is the feed control of ingredients in various processes. In an automobile, a particular ratio of "tetra-ethyl lead" to gasoline is to be maintained to produce the desired *octane number*. Feed control to a chemical reactor is another example where particular ratio of different components is to be maintained. Other examples include cement kiln speed versus slurry flow control, steam flow versus airflow in boiler control etc.

1.9 FEED FORWARD CONTROL

The purpose of feed forward control is to protect the control system against changes in loads. We measure the signals which have potential to upset the process and transmit these to the controller. The controller makes appropriate computation on the signals and calculates new required value of manipulated signal and sends it to final control element. Then the control variable remains unaffected in spite of load changes. In this case control variable is not 'fed' back but load variables are 'fed forward'. Figure 1.16 shows the block diagram of feed forward control.

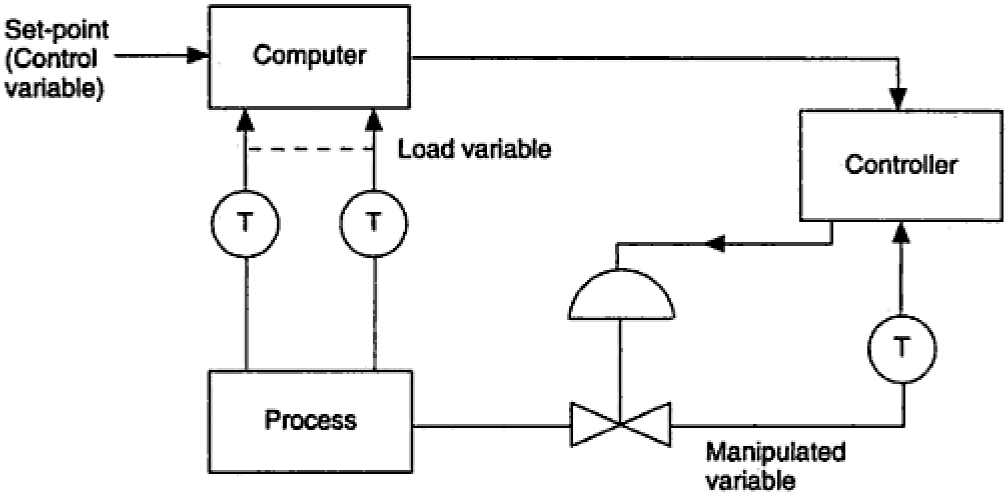

Figure 1.16 Feed forward control.

Thus, in feed forward control strategy, the information concerning one or more conditions that may disturb the control variable is converted into corrective action to minimise its deviation. In our example of cascade control of water heating system (Fig. 1.14), if load variables like temperature of input water and flow of input water change then control becomes sluggish since the temperature of water outlet will first drop and then control action will be initiated. Using feed forward control, the process disturbances may be anticipated, estimated and corrective action can be initiated even before control variable value has changed, so as to minimise the deviation.

Figure 1.17 displays the flow and temperature transmitters which measure the flow and

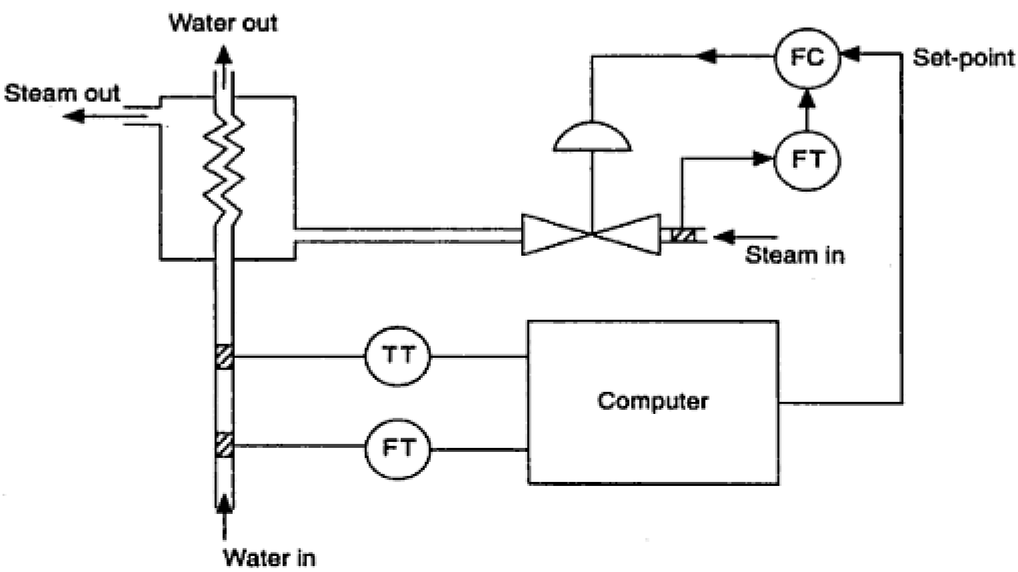

Fig. 1.17 Feed forward control of water heating system.

temperature values and later feed these to the computer. On the basis of these values (water flow, actual and desired temperature of water and set-point) the computer calculates the amount of heat required by water to acquire the desired temperature. This is used to control the steam flow. The disadvantage of feedforward control is that although there are number of variables which effect the control variables, all of these cannot be measured. In the present example heat dissipation through walls of container, inaccuracies in flow and temperature measurement are some of the variables which effect the process. In order to compensate for these inaccuracies, a feedback loop is included in the feedforward loop (Fig. 1.18).

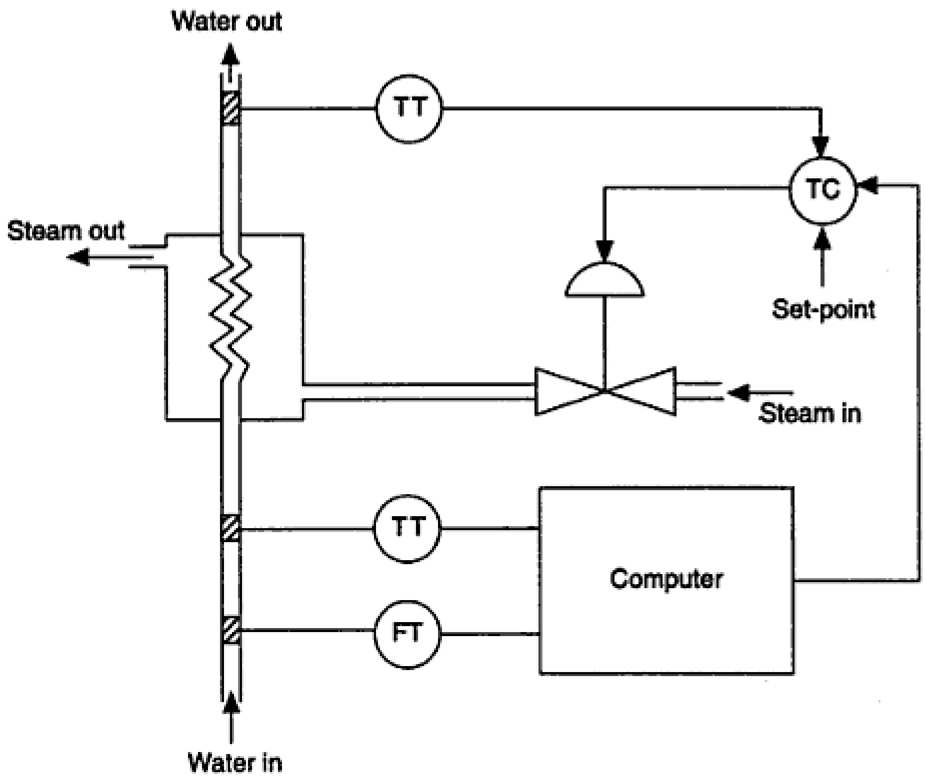

Fig. 1.18 Feedforward and feedback control combination for water heating system.

CONCLUSION

In this chapter we have introduced the basic concepts associated with the Process Control Systems. These concepts will help us in better understanding of the subsequent chapters.

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2

Transducers: Present and Future

2.1 INTRODUCTION

> I often say that when you can measure what you are speaking about and express it in numbers, you know something about it, but when you cannot measure it, you cannot express it in numbers your knowledge is meagre and or unsatisfactory kind. — Lord Kelvin

The above exhortion may appear debatable or even naive to a philosopher, to a pure mathematician or to an artist but it is of profound significance to the students of engineering and life science and to scientists and engineers.

Lord Kelvin's statement seems to spring from David Hume's or Charval's philosophy that our knowledge and understanding of the universe is nothing more than the knowledge conveyed to us through our sensors. Thus, it is to be recognized that our ability to understand and control the nature rests primarily on our ability to devise artifacts in the form of sensors which interface us to the nature enveloping us.

There are basically three kinds of transformations which are continuously occurring in the nature (Fig. 2.1). These transformations pertain to matter, energy and information. If we consider

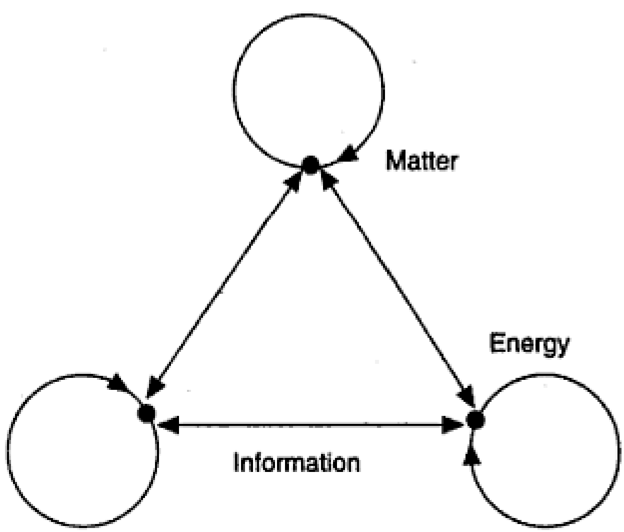


Fig. 2.1 Transformations occurring in nature.

the phenomena of conservation of energy and conservation of rate of entropy production, we find that there are only two fundamental transformations, namely, energy and information. A matter transformation can therefore be visualised as energy transformation. If we isolate the man from environment, we find that man is continuously exchanging matter, energy and information with the environment and in this manner man is an open system par excellence. In fact, man's ability to transform matter and energy is extremely limited. However, he has almost unlimited capacity of information transformation. It is this capacity which we use to devise ways and means to control other two transformations. It is also observed that all energy and information transformation occur simultaneously, i.e., they are equipresent (Fig. 2.2).

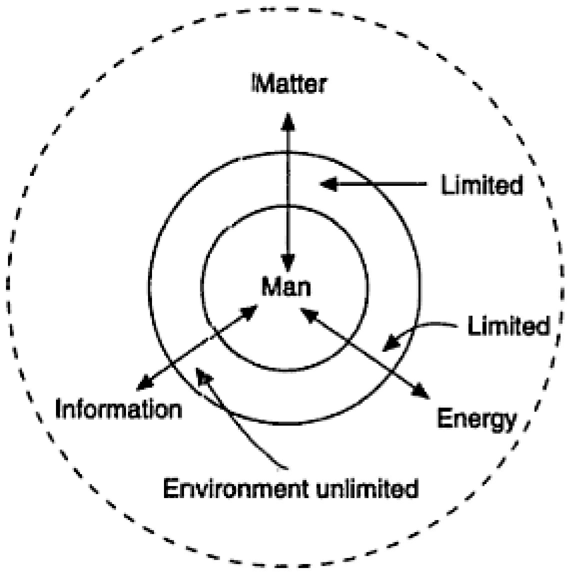


Fig. 2.2 Simultaneous occurrence of energy and information transformation.

In this chapter we shall study various types of transducers devised by man to collect information regarding nature.

2.2 TRANSDUCER—DEFINITION AND NATURE

There seems to be tremendous confusion regarding the definition of transducers. Different texts have advanced different definitions and even the various professional societies like ISA, IEEE do not give a consistent definition. What is more striking is that sometimes not only do they connote the different meanings, but also they are fundamentally wrong. For example, the widely accepted definition that transducer is an energy conversion device includes not only sensor but also actuator and even processor. By transducer we definitely do not mean a motor or a generator. For that matter this definition includes every being in a dynamic system.

Many terms like instrument, transmitter, detector are being generally used in modern industries in place of transducers. However, the only term which merit consideration as an alternate is the *sensors.*

From our discussions so far, we may deduce that the transducers should be defined as "a device which affects transformation of information from one form of energy to another".

Thus in a transducer, there is a maximum information transformation and minimum energy transformation. This definition clearly excludes transmitters, processors and actuators from its scope. However, a widely used and accepted definition of transducer that, "it is a device which provides a useful output in response to specific measurand". The measurand being a physical quantity, property or condition which is measured.

2.3 TRANSDUCER FUNCTIONS

If we analyse the above definition it is evident that the transducers perform two major functions. These are:

— to measure/to sense, and

— to convert the measurand value to a useful output.

Depending on the type of output from the first function, the conversion function may or may not be present. We will analyse these two functions separately.

2.3.1 Measurement

While selecting a transducer for any specific measurand, one should consider the following criteria:

— Type of measurand

— Number of measurements

— Sensing element

— Transduction element

— Range of measurement

2.3.2 Conversion

The conversion involves presentation of measured value in a specific format to the user. In some cases the measured value is amplified also. For example, some transducers involve the conversion of AC output from the transduction element to DC output. Some transducers even convert analog signal to digital so that they can be interfaced to computer directly.

2.4 CHARACTERISTIC OF TRANSDUCERS

2.4.1 Measurand Characteristics

A transducer is normally designed to sense the specific measurand and to respond only to this measurand. However, in some cases, measurand may even be calculated by their relationship to the measurand sensed by the transducer. For example, pressure transducer measures pressure; displacement transducer measures displacement; acceleration transducer (accelerometer) measures acceleration. However,

— displacement transducers can be used to measure position;

— displacement transducers can be used to measure velocity; and

— acceleration transducers can be used to measure velocity.

The higher and lower limits of measurand value form the range of transducer. The range may be unidirectional (0–10 psid—pounds per square inch differential), bi-directional (±3 g), asymmetrically bi-directional (–2 + 10 g) or expanded (3200 to 3800 rpm—rotations per minute). The algebraic difference between the limits of the range is called the span of the transducer. For example, the span of –2 + 10 g accelerometer is 12 g.

2.4.2 Electrical Characteristics

Transducers normally produce analog output in the form of current, voltage ratio, voltage amplitude or variation of other parameters such as capacitance, inductance etc. The output can also be produced in the form of frequency (for example: 0 to 1224 Hz) or in the form of binary numbers which represent the output of transducers in digital era. Normally all transducers (except self-generating types, for example electromagnetic, piezoelectric etc.) require external electric excitation in the form of AC/DC voltage or current. The impedance (Z_{in}) measured across the excitation terminal is called the input impedance and across output terminals, the output impedance (Z_s) of the transducers (Fig. 2.3). The load impedance (Z_L) is the impedance presented at the transducers output by external circuitry and transmission line. Mismatch at Z_L and Z_{in} causes load errors.

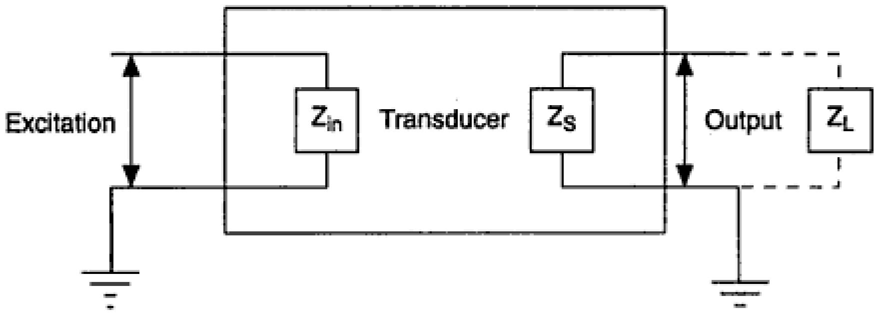


Fig. 2.3 The input output, and load impedance across the excitation terminal.

The transducer with built in rectifier to convert AC to DC voltage output will present ripple in the DC output. In case a transducer is having integral amplifier, then amplifier characteristics are reflected at the output. These include output noise in the form of harmonics, gain instability and recovery time.

2.4.3 Static Characteristics

Transducer characteristics which are determined during a calibration cycle at room conditions are called static characteristics. To determine static characteristics, transducer calibration is performed in indoor conditions in the absence of acceleration, shock or vibration.

Accuracy and precision

Every transducer is expected to follow an ideal or theoretical output/measurand relationship. However, due to practical limitations the output of transducer is affected by the non-ideal behaviour. It causes the indicated measurand value to deviate from the true value. The difference between these two values is called transducer error which is normally expressed in percentage of Full-Scale Output (% FSO). The accuracy of a transducer is defined as the ratio of the error to the full-scale output.

Precision is the closeness with which measurements are distributed about their mean value. It refers to the degree of agreement on a set or group of measurements.

Repeatability

The ability of transducer to reproduce output relation and same measurand value, when it is applied consecutively under the same conditions in the same directions is called the repeatability of a transducer.

Linearity

The closeness of a transducer calibration curve to specify a straight line is called the linearity of transducer. The transducers are designed with linear output/measurand relationship as this tends to facilitate data reduction.

Resolution

Output of transducers normally change in small discrete steps when the measurand is varied over the range. The magnitude of these output steps (called resolution when expressed in % FSO) is different at various steps in different ranges. Due to this reason, resolution is normally expressed as maximum resolution as the greatest of all the steps. Figure 2.4 shows the difference between accuracy and resolution in case of shooting. A transducer should possess both high resolution and high accuracy at the same time.

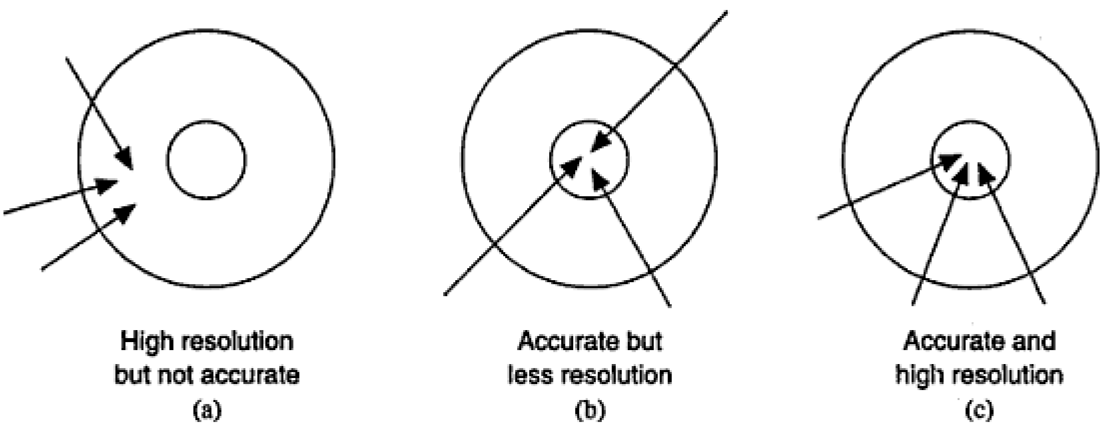


Fig. 2.4 Difference between accuracy and resolution in case of shooting.

2.4.4 Environmental Characteristics

When the transducer operates under the conditions which are different from the room conditions, a number of errors can appear in the transducer output.

The environmental conditions of the transducer for storage, shipping and operation are well specified. Errors caused due to change in environmental conditions are called environmental errors. Environmental effects on transducers are normally temporary, i.e. transducers will start functioning normally as soon as operational environmental conditions are restored. However, in some cases the transducer can get damaged or its characteristics may get permanently changed.

2.5 TRANSDUCER CLASSIFICATION

There are several criteria on the basis of which transducers have been classified. We shall discuss here about these major criteria.

2.5.1 Classification Based on Energy

All electrical transducers have been classified under two categories: (a) Active transducer, and (b) Passive transducer.

Active transducers are self-generating type. They do not require electric energy. They work on the principle of conservation of energy. For example, thermoelectric and piezoelectric devices. *Passive transducers* are based on principle of energy controlling and they require a secondary electrical source for operation, for example strain gauge devices.

2.5.2 Classification Based on Technology

Transducers have also been classified on the basis of technology used for their design. For example, they are categorised as mechanical transducers, electrical transducers, electronic transducers etc.

2.5.3 Classification Based on Measurand

The transducers are classified by the 'measurand type' they are supposed to measure. For example, pressure transducers, displacement transducers etc.

Unfortunately, there is no standard way for the transducer classification but the classification based on the measurand type is most common in practice. We shall use this type of classification while describing the various types of transducers available today. The terms sensor and transducer have been used interchangeably in the book.

2.6 TECHNOLOGY TREND

2.6.1 Conventional Transducers

The transducer technology is quite varied in nature. Conventional technology uses the electric and electromechanical principles to sense various measurands. Linear Voltage Differential Transformer (LVDT) uses the inductance principle to measure the displacement/position. To measure temperature, the principle of change in resistance is used for RTD (Resistance Temperature Detector) and thermistors, whereas thermocouples use Seebeck's principle of thermoelectricity. Table 2.1 illustrates the conventional transducer technology in case of pressure and temperature.

2.6.2 Silicon Transducers

Silicon is known to be highly effective material for transducing many physical parameters including light levels, force and temperature. Silicon process technology is highly developed and well suited to high volume production. Work on high performance linear circuits, such as data converters has revealed that technology is capable of high precision, required for many sensing applications. Since transducers are devices producing low level analog output, some signal conditioning (e.g. amplification or encoding) is often required before transmission to digital world of computer. The designer will have an additional degree of freedom with silicon sensors which enable to integrate signal conditioning circuitry into the transducer chip.

Table 2.1 General Pressure and Temperature Sensing Techniques

Transduction method	Principle of operation	Range	Approximate accuracy error	Advantages	Disadvantages
Pressure					
Capacitive	Deflections of pressure diaphragm acting as one plate of a parallel plate capacitor cause capacitance changes	0.01 to 200 psi	0.05%	High accuracy and sensitivity; ruggedness; temperature insensitivity	High cost; unsuitability for high pressure
Inductive	Deflections of pressure diaphragm or Bourdon tube cause inductance changes in inductance bridge or differential transformer	0.04 to 10000 psi	0.5%	High outputs; wide pressure range	Instability with temperature; susceptibility to shock and vibration
Piezoelectric	Pressure on a quartz or Rochelle-salt crystal produces an electrostatic voltage across it	0.1 to 10000 psi	1%	No need for excitation; wide frequency-response, pressure, and temperature ranges.	Low output and accuracy instability
Piezoresistive (strain gauges)	Pressure induced strain in sensing element causes resistance change in gauges	0.5 to 10000 psi	0.25 to 0.5%	High sensitivity low hysteresis and cost (semiconductor types); ruggedness; wide temperature range	Low output; temperature sensitivity
Temperature					
Thermoelectric (thermocouple)	Electromotive force is generated at the junction of two dissimilar metals, each at a different temperature	−200 to +2000°C	1 to 5%	Wide temperature range; high temperatures	Low output accuracy, and sensitivity; instability; high cost
Resistance (thermistors resistance temperature detectors)	Resistance changes because of temperature in metal oxides of metallic conductors	−100 to +400°C	1 to 10%	(Thermistors) high output and sensitivity; low cost (RTDs) high accuracy, and linearity; wide temperature range	(Thermistor) nonlinearity; small temperature range (RTDs) high cost; long thermal time constant
Semiconductor diode	Base-emitter voltage of a forward-biased diode changes with temperature	−55 to +200°C	0.1 to 1%	High accuracy, stability and linearity; low cost range	Low output; limited upper-temperature

The silicon sensors are rugged as well. The Young's Modulus of elasticity for silicon is greater than that for steel. This makes these sensors suitable for industrial applications. The analog signal outputs of transducers are converted to digital by Analog to Digital Converter. The digital information is then further processed by computer. Silicon sensors with on-chip signal conditioning and Analog to Digital Converter will soon start appearing in the market.

The development of silicon sensors fabricated using IC batch processing technology has spurred by space research and bio-medical applications in the late 1980s. Taken with the advances in LSI fabrication techniques, this development held the promise that a family of sensors for a variety of parameters could be fabricated in silicon at extremely low cost. As many as dozen firms, have pursued this path.

2.6.3 Fibre-Optic Transducers

It has been well established that the communication via optical fibres confers many advantages over the more conventional metallic cable systems and these include,

— high information density over long distances;

— low losses;

— light weight;

— economy of the material with respect to metallic conductor like copper; and

— immunity from electromagnetic and atmospheric interferences such as fog, smog, rain and snow.

In the field of fibre-optic communication, problems due to high sensitivity of fibres to external influences like phase sensitivity, microbending losses and model noise are encountered. In the field of sensor technology, the same problems are exploited to develop sensors. Fibre-optic sensors have assumed considerable importance in instrumentation in recent years due to the following advantages:

1. High sensitivity as compared to other sensors.

2. Geometric versatility of sensors, which enables the realization of any arbitrary shape for them.

3. Common technology base from which sensors for various parameters can be realised, e.g. sensors for acoustic, magnetic, thermal, and mechanical measurement are possible using fibre-optics.

4. Simplicity of technology

5. Ease of signal transmission over long distance.

Basically a fibre-optic sensor comprises of a Light Source (e.g. LASER, LED etc.), injecting a signal into sensor fibre, a Light Detector (e.g. Photodiode) for receiving the signal after the light has been modulated by the sensor fibre and an electronic system for processing the detected signal into useful electrical quantity (Fig. 2.5).

Figure 2.6 illustrates types of fibre-optic sensors now being developed. Of these, first system which uses optical sensors element combined with fibre-optic signal transmission line, is the least developed and it is on this type of system that research is being concentrated. The second type of system is reflective optical sensor which senses changes in a beam of light between fibre ends at a gap in the transmission line. The third system is a discrete optical sensor with a fibre-optic

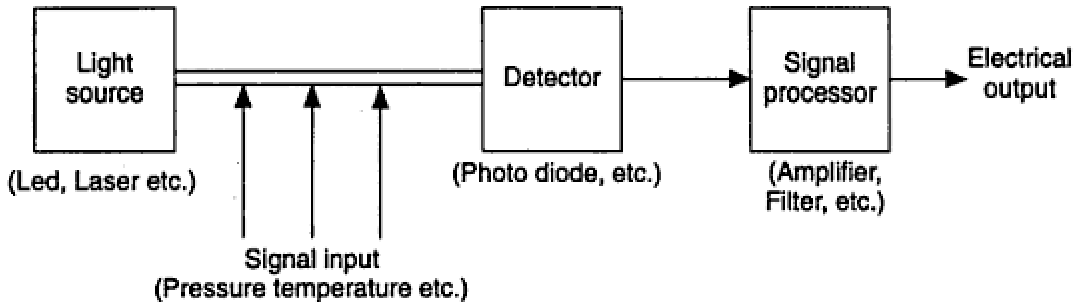


Fig. 2.5 Schematic diagram of a fibre-optic sensor.

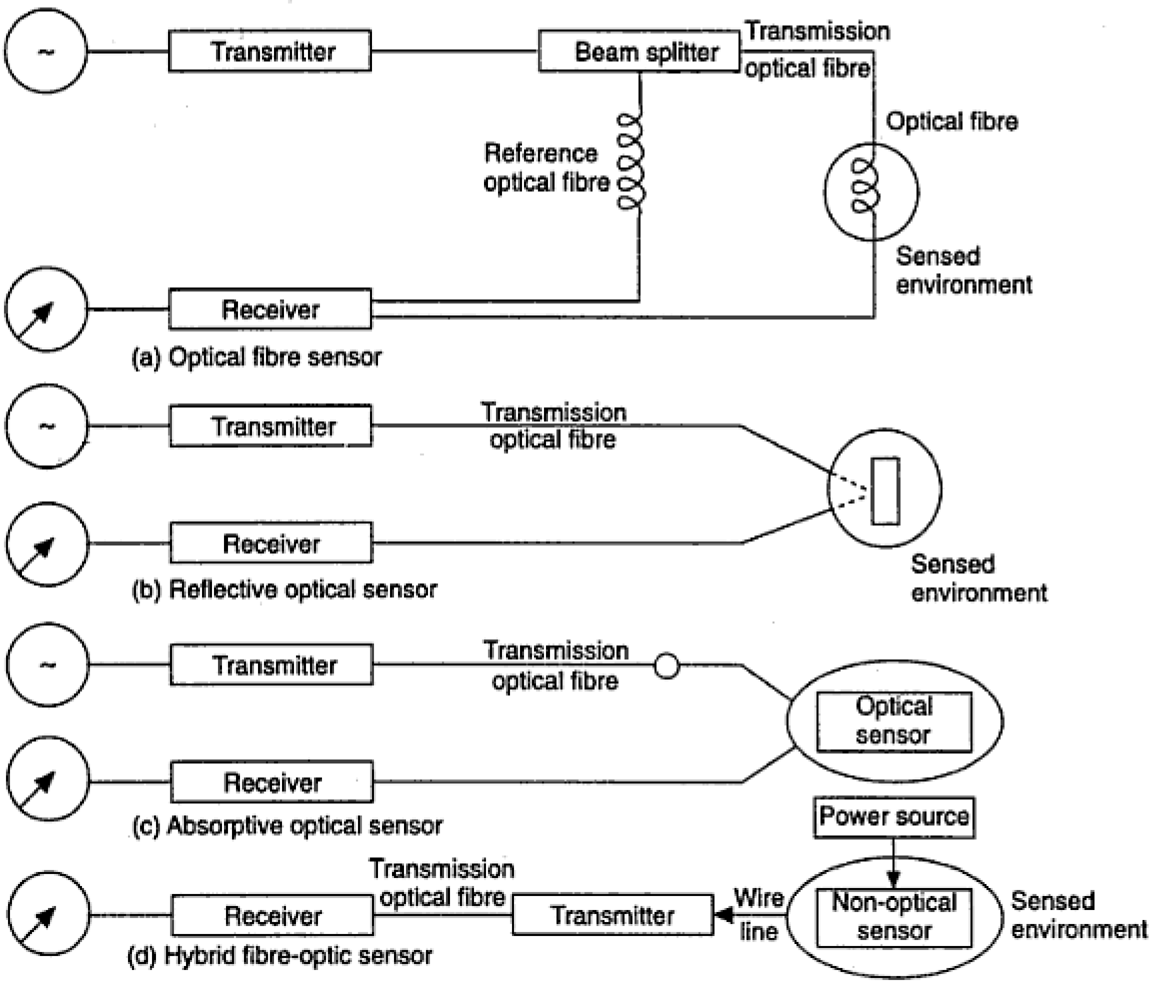


Fig. 2.6 Typical fibre-optic sensors.

transmission line. This is also known as absorptive optical sensor. The final type is a discrete non-optical sensor element, with the fibre-optic transmission line. It is also known as hybrid fibre-optic sensor.

2.7 DISPLACEMENT/MOTION TRANSDUCERS

The displacement and motion of a body can be measured in many ways. The transducer may work on the principle of potentiometer, inductor, the reluctance, capacitor and even piezoresistance.

2.7.1 Linear Variable Differential Transformer (LVDT)

LVDT transducer is primarily used to measure the linear displacement. It comprises a transformer with one primary and two secondary coils with a movable core between them. The schematic diagram of LVDT is shown in Fig. 2.7.

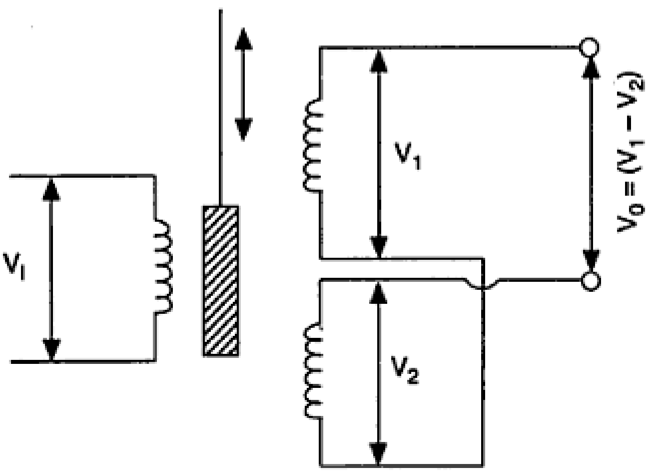


Fig. 2.7 A schematic diagram of LVDT.

The secondary coils are identical and positioned symmetrically with respect to the primary coil. These coils are connected in opposite phase. The movable core is connected to the member whose displacement is to be measured. When the core is at centre, the voltages V_1 and V_2 in both the secondary coils are equal. Thus output voltage V_0 is zero, when displacement is zero. When the core is displaced, then V_1 and V_2 are different due to asymmetry of the core location with respect to secondary coils. This causes a finite non-zero output V_0.

The output voltage V_0 is linear with displacement over a wide range. It undergoes a phase shift of 180 degree when core passes through zero displacement position, as shown in Fig. 2.8. Residual voltage V_r at zero displacement is normally 1% or less of maximum linear voltage. This is caused by stray magnetic and capacitive effects. Residual voltage can be reduced by providing adequate grounding or by balancing the output circuit with resistive and capacitive shunt. Low pass filter at input will also help in the reduction of residual voltage. Figure 2.9 shows a cross-section of an LVDT. Commercial LVDT transducers have a range from 0.001 to several inches. However detection of microinches displacement can also be made by certain special types of LVDTs.

2.7.2 Capacitance Gauges

A simple capacitance gauge for displacement measurement consists of a pair of equal area parallel plates. One of the plates is movable while the other is fixed. The movable plate is connected to the member whose displacement is to be measured. The capacitance C between the

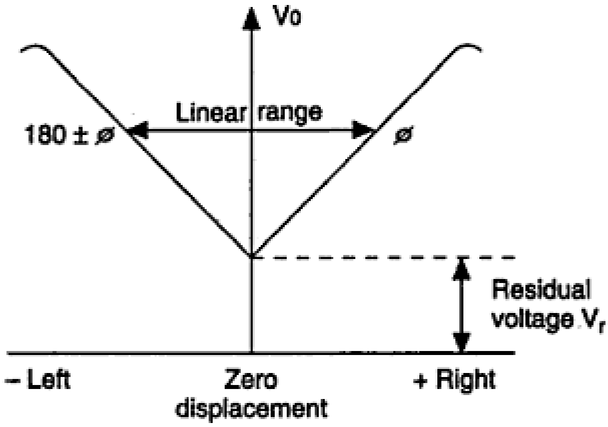


Fig. 2.8 Illustration of LVDT undergoing a phase shift of 180 degree when core passes through zero displacement position.

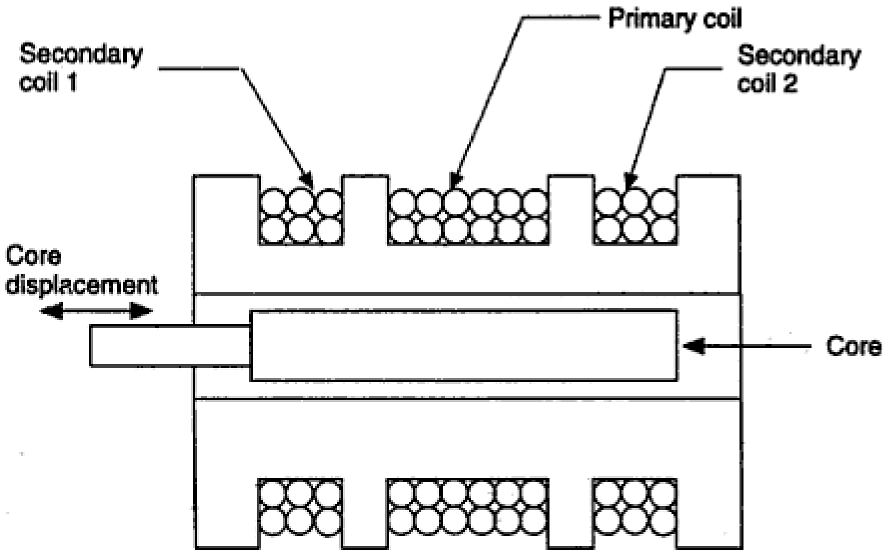


Fig. 2.9 A sectional view of a linear variable-differential transformer (LVDT) (Gulton).

plates is given by:

$$C = K \cdot E \cdot A/X$$

where

A = area of plate;
K = constant (the value being 0.0885 when dimensions are expressed in centimetres and 0.225 when dimensions are expressed in inches);
E = dielectric constant;
X = distance between plates.

The displacement in the movable plate changes the distance between the plates thus changing the capacitance. The change in capacitance (and thus displacement) can be measured by connecting an AC voltage source and measuring the change in voltage.

However, normally differential capacitor is used for displacement measurement. Figure 2.10 shows a schematic of differential capacitance gauge.

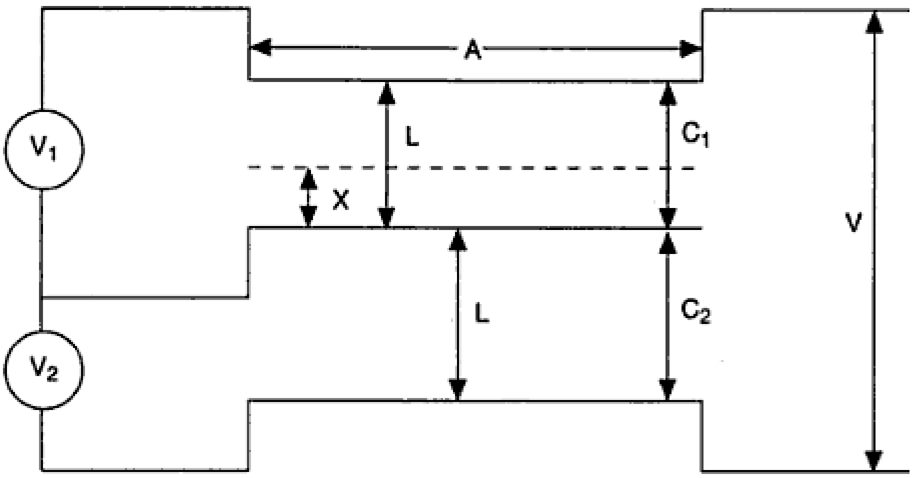


Fig. 2.10 A schematic of differential capacitance gauge.

In normal position when displacement is zero, the capacitances C_1 and C_2 are equal. The middle plate is movable and the distance of middle plate from the two other plates is equal, when displacement is zero.

$$C_1 = C_2 = K \cdot E \cdot A/L$$

The displacement input changes the position of centre plate with respect to other plates. For a displacement "X" of centre plate towards plate 1.

$$C_1 = K \cdot E \cdot A/(L - X), \quad C_2 = K \cdot E \cdot A/(L + X),$$

$$V_1 = VC_2/(C_1 + C_2) = V(L - X)/2L, \quad V_2 = VC_1/(C_1 + C_2) = V(L + X)/2L$$

$$\text{Difference voltage } V_0 = V_1 - V_2 = VX/L$$

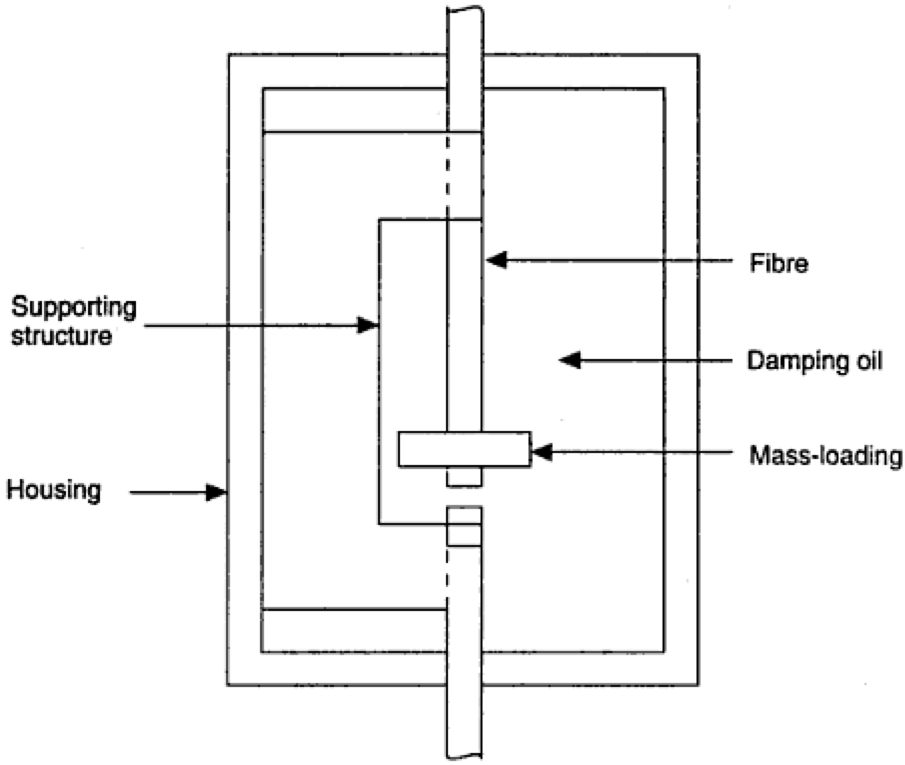
Thus, V_0, the difference voltage is linear function of displacement X. The outputs V_1 and V_2 of the two capacitors are fed into a differential measuring circuit to obtain difference voltage.

2.7.3 Silicon Displacement Transducers

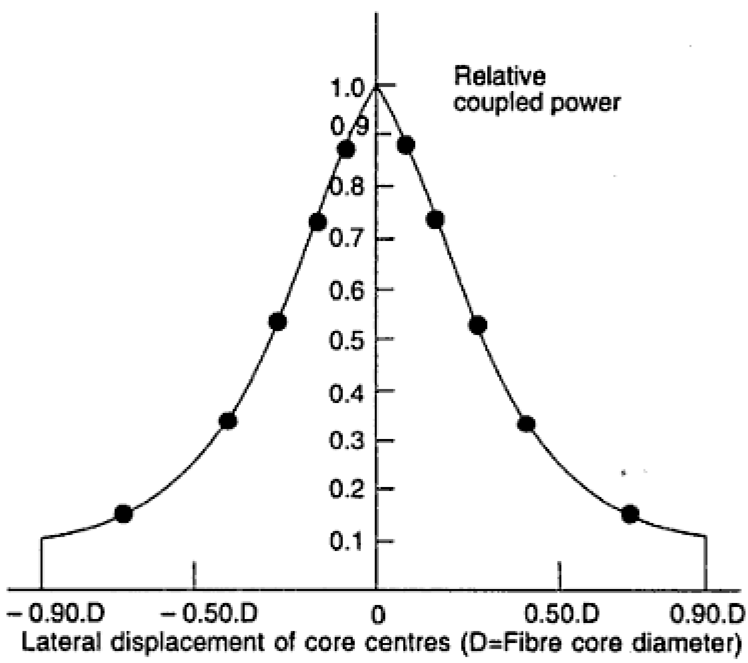
Many silicon pressure transducers discussed later can be used to measure the displacement also. KEZ10 silicon pressure transducer from Philips has been used to measure extremely small displacements (20 to 50 µm). Philips also offers KMZ10 silicon position sensors working on magnetoresistive principle. It can be used to measure both linear as well as angular displacements, from a few millimetres up to tens of centimetres with resolution up to 1 micrometre (µm). Hall effect silicon transducers have also been used for this purpose.

2.7.4 Fibre-Optic Displacement Transducers

Mechanical Technology Inc., USA introduced an optical displacement transducer in 1967. It uses light reflection technique which is still in use for vibration analysis and some other applications. A scheme for the measurement of displacement is shown in Fig. 2.11. This cantilever type fibre-optic displacement sensor has been developed at Sanders Association Inc. for acoustic hydrophone applications. A multimode fibre is mounted as a mass loaded cantilever bar. There is an output fibre to form an optical transmission path by aligning itself to cantilever fibre. The cantilever fibre



(a)



(b)

Fig. 2.11 A fibre-optic linear accelerometer: (a) Device configuration, and (b) Response curve a function of lateral displacement.

is connected to the subject. Any lateral displacement in cantilever fibre will result in misalignment between two fibre end surfaces. This will change the intensity of light in the output fibre.

General Electric Research laboratory has developed optical transmission grating for measurement of displacement. Two optical fibres (Fig. 2.12) are coupled through two optical transmission gratings, one of which is stationary and other is movable. The movable grating is connected to the subject. The movable gratings act like a shutter between the two fibres. The amount of light that can pass from input to output fibre is linearly proportional to lateral displacement between two gratings.

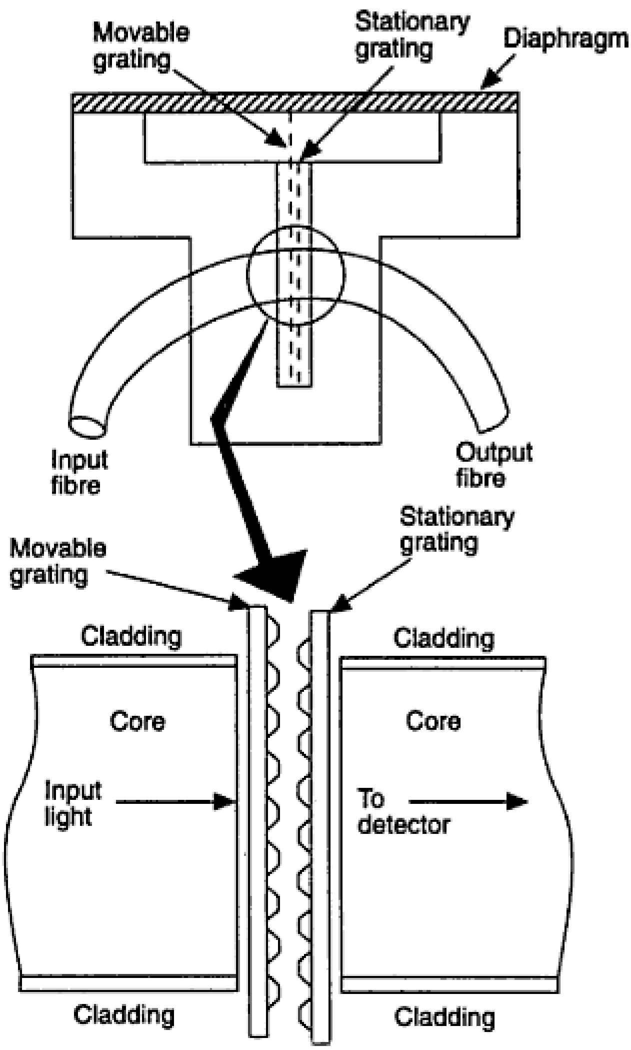


Fig. 2.12 Moving grating hydrophone.

Displacement sensors based on twisting or bending of optical fibre has been developed at TRW (USA). When an optical fibre is bent, the transmission loss increases since the optical modes are coupled out from the core region into the cladding region of the fibre. An optical fibre is placed between two corrugated plates as shown in Fig. 2.13. The loss during light transmission is measured and the displacement is derived from that.

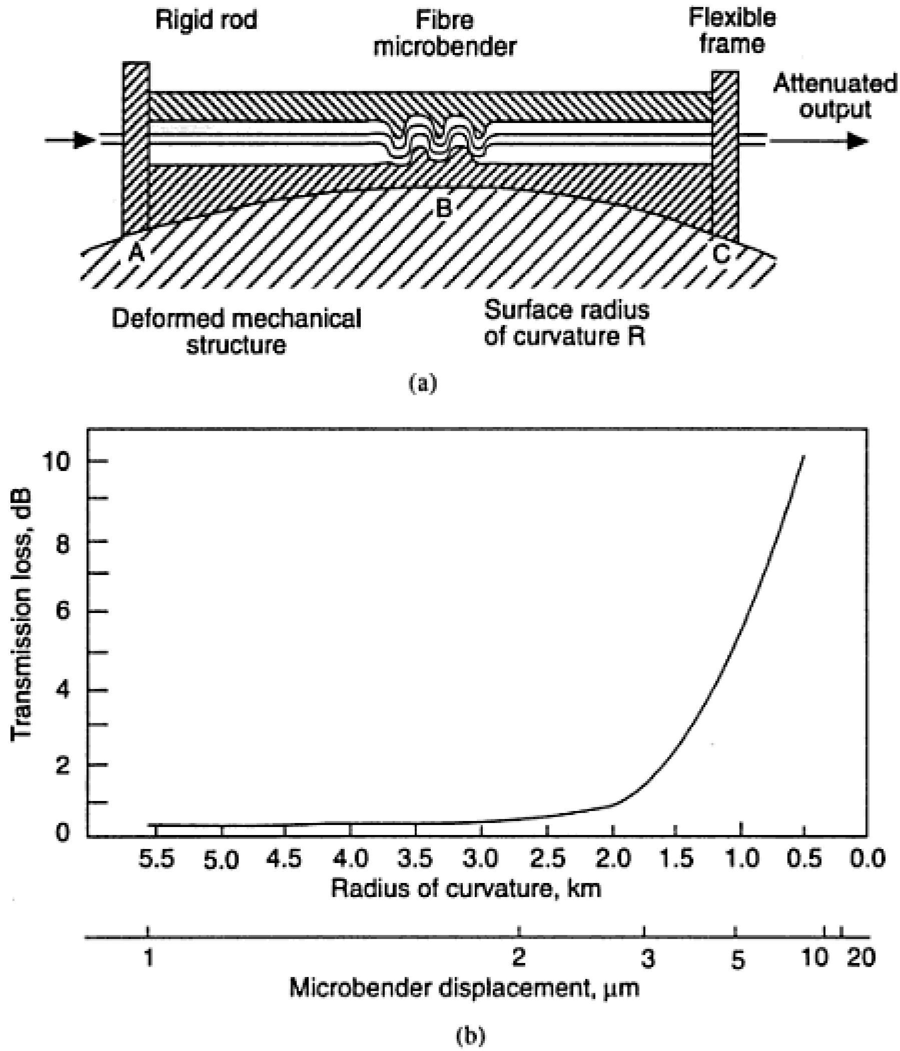


Fig. 2.13 (a) A microbending fibre-optical sensor, and (b) Response curve of sensor.

A commercially available device for displacement measurement using optical fibres is based on light collection in a broken optical fibre path (Fig. 2.14). The light launched from input fibre is reflected by the surface and collected by the output fibre. The amount of light collected depends on the gap between the fibre end surface and the reflecting surface. The change in amount of light collected in the output fibre is detected, in order to measure the displacement of reflecting surface which is connected to the subject.

2.8 TEMPERATURE TRANSDUCERS

The temperature measurement involves the expansion properties of solid, liquid or gases or changes in electrical properties of certain materials. For very high temperature, the colour change is taken as a interim for measurement. The temperature is thus dependant parameter since material property is involved in its measurement.

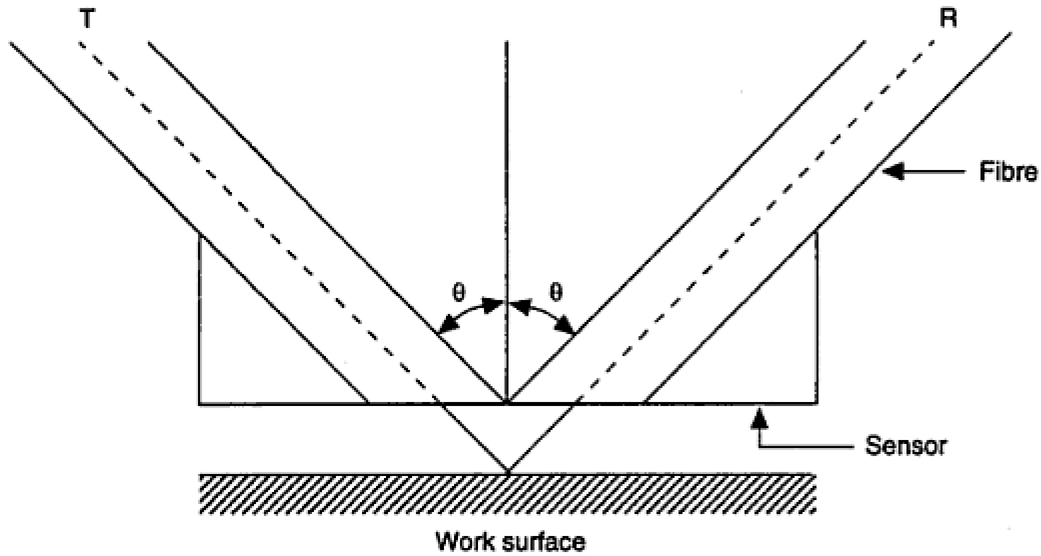


Fig. 2.14 Fibre-optical displacement sensor.

The bimetal thermometer, filled in thermometric system and vapour pressure thermometer are examples of temperature transducers which involve the expansion properties of solid, liquid and gas respectively. The examples of electrical temperature transducers are resistance thermometers, thermocouples, thermopiles and so on etc. The optical methods are used for very high temperature transducers.

2.8.1 Resistance Temperature Detector

The Resistance Temperature Detector (RTD) is based on the principle that the resistance of a metal changes with temperature. Generally platinum and nickel are used as metal in RTD's. The relation between temperature change and metal resistance is given by

$$RT = R_0(1 + \alpha \Delta T)$$

where

R_0 = original resistance,
RT = resistance when a temperature difference ΔT is applied,
α = temperature coefficient of the metal.

Generally platinum (–190 to 660°C) and nickel (0 to 325°C) are used as metal in RTDs.

The resistance wire diameter may vary from 0.002 to 0.06 cm depending on the range. The wire is tested for purity and wound on a framework to form a coil. Different frameworks are chosen for different kinds of applications (Fig. 2.15). For instance, a mica-cross is used for general purpose application, whereas for surface temperature measurement a strain gauge type mesh may be used. In case of measurement of temperature of flowing liquid/air as self-supporting helical form is more useful.

A variety of materials are used in the production of resistance temperature detector. Common among these are nickel, nickel-iron alloy, copper and platinum. Due to extra stability, platinum is popular, and 100 ohms platinum sensor is perhaps the most widely used RTD. Thin film RTDs are recognised for their long term stability.

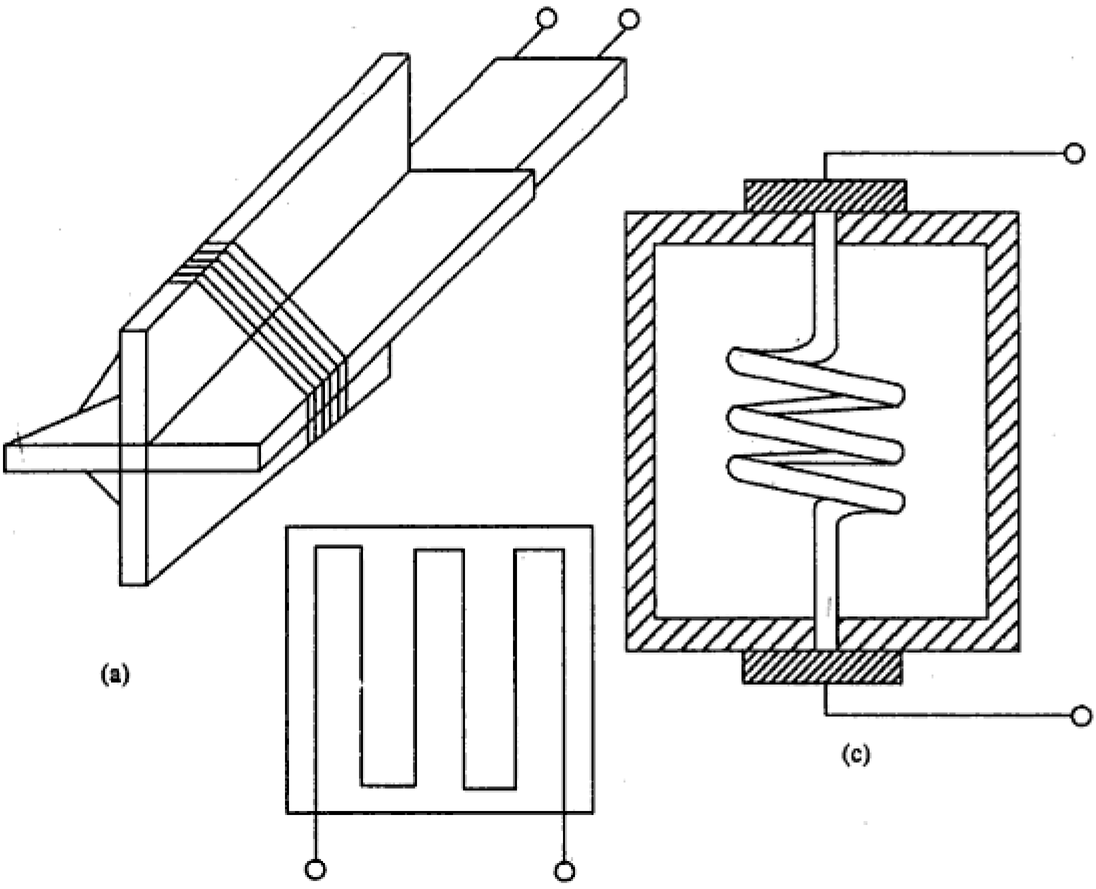


Fig. 2.15 Types of resistance elements for measuring temperature: (a) Mica-cross winding type, (b) Strain gauge (mesh) type, and (c) Self-supporting helical type.

The resistance temperature detectors are most accurate of all temperature transducers. An accuracy of 0.0001 degree centigrade can be achieved by these transducers and these are very convenient for small temperature differences. However, they have inherent drawbacks of heat loss, i.e. self-heating error ($= I^2RT$), thermo e.m.f. and requirement of separate power pack.

2.8.2 Thermocouples

Thermocouples are the most important temperature transducers in the industry applications. They work on the Seebeck's principle of thermo e.m.f that when two dissimilar metals are joined as shown in Fig. 2.16 with the two junctions J_1 and J_2 at temperatures t_1 and t_2 respectively, then an e.m.f. is generated, causing a current to flow in the circuit.

The relation between the output voltage (in millivolt) and junction temperature has been found empirically as,

$$E = \sum_{n=1}^{k} \frac{1}{n} \cdot \alpha \cdot t^n$$

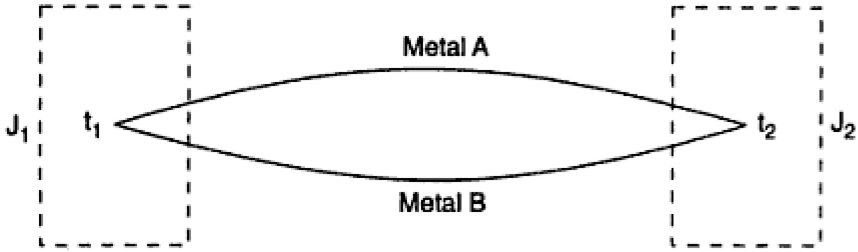


Fig. 2.16 Seebeck's principle of thermo e.m.f.

The term t is the hot junction temperature when the cold junction is maintained at 0°C. In practice $K = 3$ has been found sufficient. The constant α depends on the materials of thermoelements (metals). For appropriate measurement, the linear relation between E (output voltage) and t (hot junction temperature) will be required with high sensitivity.

Following are the most commonly used industrial thermocouples:

S. No.	Type	Combination	Temperature Range
1.	T	Copper-Constantan	– 180 to 370°C
2.	J	Iron-Constantan	0 to 760°C
3.	K	Chromel-Alumel	0 to 1260°C
4.	R	Platinum- Platinum	0 to 1480°C
	S10	Rhodium	

Type J thermocouples are useful in the environment where there is a lack of free oxygen. Unprotected type J thermocouples may be used up to 290°C in reducing atmosphere. Heavier wire and protection wells should be used for 540 to 870°C temperature measurement. Type K on the other hand is suitable for oxidizing atmosphere where excess of free oxygen is present. Types R and S10 thermocouples are called noble metal thermocouples and are used for higher temperature ranges. These should be protected by impervious tubes when used at temperature above 540°C.

The main problem encountered with thermocouples is the low signal level. The electrical noise on the signal lines is quite higher than the temperature signal. Thus measuring device should have a high input impedance and very high common mode noise rejection.

Industrial thermocouples have only one junction, the hot junction which is connected to the process. The cold junction or reference junction is at ambient temperature. This requires compensation. The assumption that the cold junction is at constant temperature does not hold in the industrial environment. This also requires compensation and is called *cold junction compensation*.

A practical approach for cold junction compensation is to measure the temperature of cold junction by an RTD or thermistor and correct the termocouple indicated temperature. This can be done by determining and adding a correction temperature to the instrument or by modifying the thermocouple signal directly.

Thermocouple tables are provided by the manufacturers. The tables show the voltages obtained at various temperatures. Table 2.2 shows a part of table for type R thermocouple referenced to cold junction at 0°C. We shall illustrate the cold junction compensation using this table.

Table 2.2 Extract from Thermocouple Tables for Type R (platinum-platinum/13% rhodium) (Referenced to cold junction at 0°C. Voltage in μV.)

	Temperature (°C)									
	0	1	2	3	4	5	6	7	8	9
0	0	5	11	16	21	27	32	38	43	49
10	54	60	65	71	77	82	88	94	100	105
20	111	117	123	129	135	141	147	152	158	165
800	7949	7961	7973	7986	7998	8010	8023	8035	8047	8060
810	8072	8085	8097	8109	8122	8134	8146	8159	8171	8184
820	8196	8208	8221	8233	8246	8258	8271	8283	8295	8308
830	8320	8333	8345	8358	8370	8383	8395	8408	8420	8433
840	8445	8458	8470	8483	8495	8508	8520	8533	8545	8558
850	8570	8583	8595	8608	8621	8633	8646	8658	8671	8683
930	9589	9602	9614	9627	9640	9653	9666	9679	9692	9705
940	9718	9731	9744	9757	9770	9783	9796	9809	9822	9835
950	9848	9861	9874	9887	9900	9913	9926	9939	9952	9965
960	9978	9991	10004	10017	10030	10043	10056	10069	10082	10095

1. Let us assume that ambient temperature T_2 measured by thermistor is 25°C and thermocouple voltage is 8.46 millivolt (mV).

2. The table shows thermocouple voltage of 0.141 millivolt (mV) for 25°C temperature.

3. Corrected voltage = Thermocouple voltage + voltage corresponding to ambient temperature.
$$= 8.46 + 0.141 = 8.601 \text{ mV}.$$

4. From table voltage 8.595 mV corresponds to 852°C and voltage 8.608 mV corresponds to 853°C. The actual temperature can be found by interpolation.

1°C difference = 8.608 − 8.595 = 0.013 mV.

Thus (8.601 − 8.595) = 0.006 mV and temperature correction $= \dfrac{0.006}{0.013}$
$$= 0.46°\text{C}$$

Thus corrected temperature = 852°C + 0.46°C
$$= 852.46°\text{C}$$

Figure 2.17 shows the basic thermocouple circuit in temperature measurement. The load

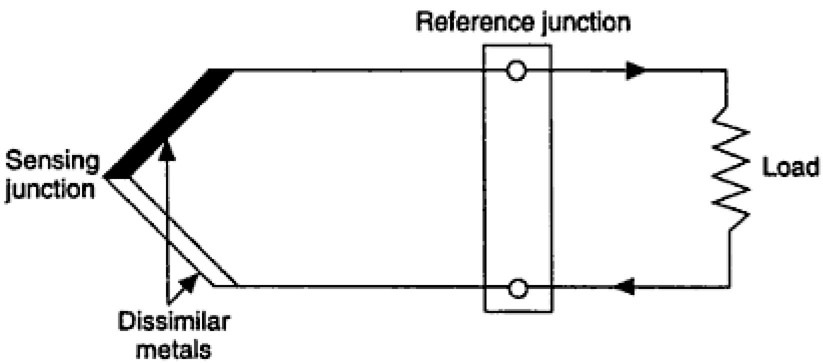


Fig. 2.17 Basic thermocouples circuit in temperature measurement.

generally consists of signal conditioning circuit. The temperature difference between sensing junction and reference junction causes a current to flow through the load.

2.8.3 Thermistors

Thermistors are semiconducting resistance temperature transducers, with large coefficient of resistance. The negative thermistors are more common in the industry than positive thermistors (limited to 50 to 225°C range). The relation of a negative temperature resistance coefficient is shown in Fig. 2.18. The non-linear scale over the entire range of operation may be made linear by applying various compensation schemes. A single low resistance in parallel to the thermistor will reduce the sensitivity but increase the linearity, as shown in Fig. 2.19.

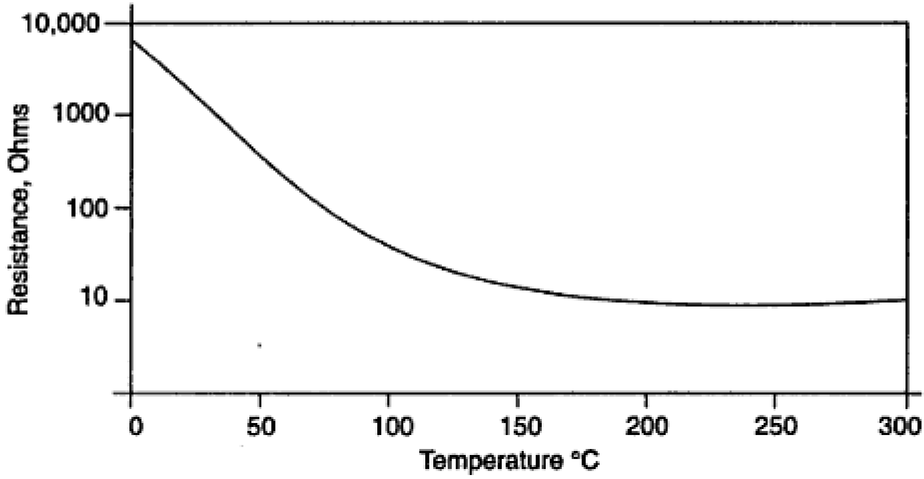


Fig. 2.18 The non-linear relation of a negative temperature resistance coefficient.

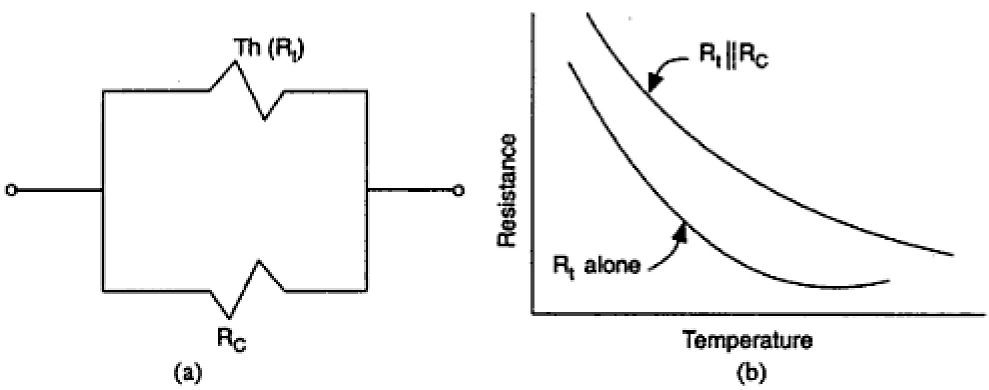


Fig. 2.19 Compensation for non-linearity of thermistor response: (a) Scheme of paralleling with a low resistance, and (b) Response curves of uncompensated and compensated thermistor resistances.

Oxides and sulphides of copper, cobalt, manganese etc. are used in the manufacturing of thermistors. The bead, rod and disc type thermistors are more common (Fig. 2.20). The thermistor range for common purpose is specified as from 100 to 300°C. However, special thermistors made of aluminum oxide cover a high temperature range from 800 to 1000°C.

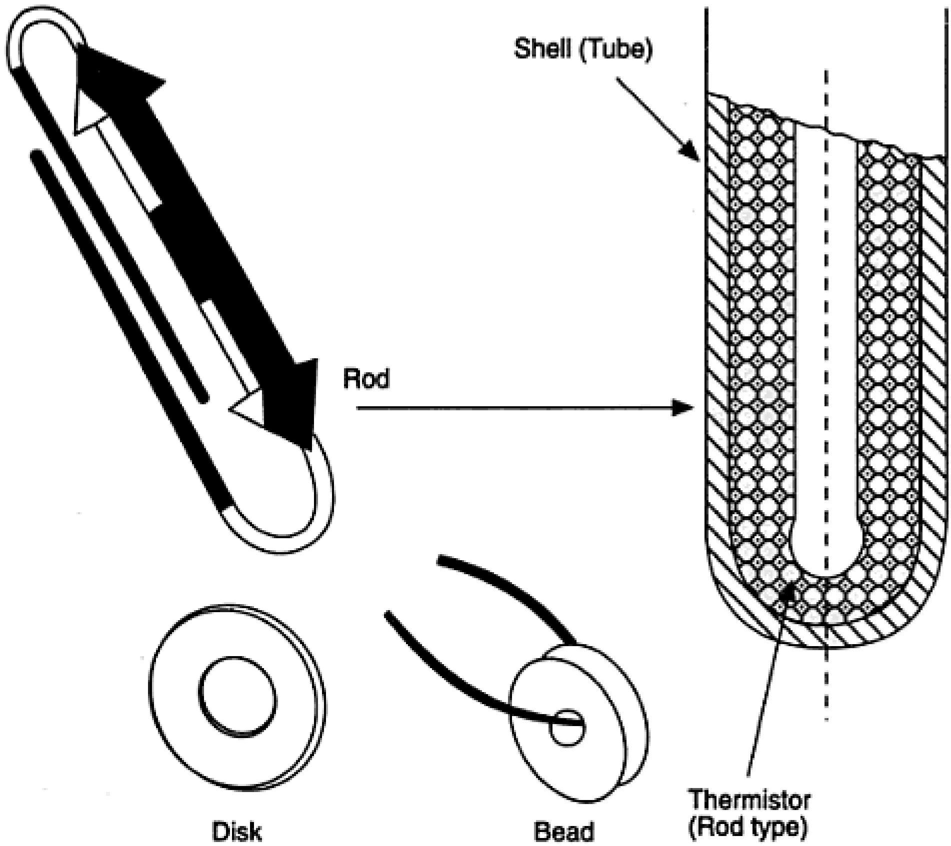


Fig. 2.20 The bead, rod, and disk type thermistors.

2.8.4 Pyrometers

Pyrometers are used when the measurement transducers cannot be put into contact with the process. It may be due to very high temperature (as in blast furnace) or hot mobile bodies (as in case of rolling mills). The basic principle of measurement through pyrometers is to measure directly or by colour comparison the energy radiated by the hot body. In case the radiated energy is measured directly, it is called radiation pyrometery and when the energy is measured by colour comparison, it is called optical pyrometery.

2.8.5 Radiation Pyrometers

Figure 2.21 shows the principle of radiation pyrometery. The radiations emitted by the hot body are focused on a thermal detector element using a focusing lens. The voltage produced by the detector follows the empirical relation given below

$$V = K_v\, T^n$$

where

$3.5 < n < 4.5$
V = output voltage,
T = temperature of hot body,
K_v = constant.

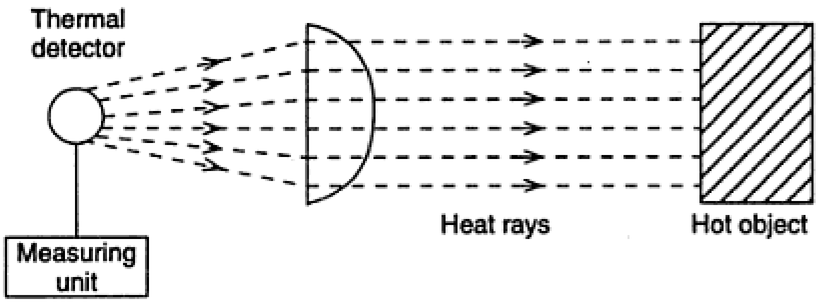


Fig. 2.21 Illustration of principle of radiation pyrometery.

The value of K_v is obtained from experimental calibration. Commonly used thermal detectors are thermopiles, photocells, thermistors etc.

2.8.6 Optical Pyrometers

The basic principle of optical pyrometers is shown in Fig. 2.22. The radiation received from the hot object are focused on a filament by means of a lens. The filament is viewed by a microscopic system. The image of the target is formed at the filament position and the filament is viewed in a direction against the background of the target surface. The brightness of filament is adjusted till it disappears from the field of view. The current flowing through the filament may be measured. In fact the ammeter connected in series with the filament may be directly calibrated to give temperature of target.

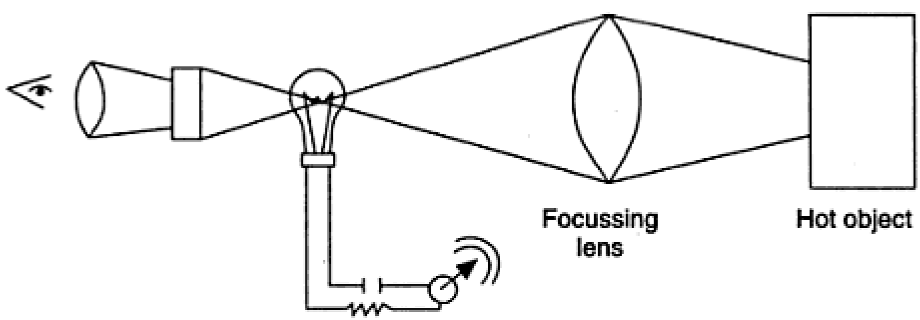


Fig. 2.22 Basic principle of optical pyrometers.

Optical pyrometers are usable in the range between 700 to 3000°C and are more accurate than radiation pyrometers. The lower temperature range is limited due to limitation of human eye to compare the radiation sources. However, automatic optical pyrometers are also available for measurement and control. Figure 2.23 shows an operational diagram of automatic optical pyrometer (*Courtesy:* Leeds and Northrup Co).

The multiplier phototube collects the radiations from target and standard lamp alternately, through rotating light modulator disc. If the brightness of the two sources is not same then a signal is fed to the lamp through preamplifier, demodulator and integrator. The integrator drives the standard lamp circuit, so that the brightness of lamp equals that of hot object. An automatic gain control is provided to prevent the measuring system becoming over sensitive at higher temperatures. Automatic gain control varies the demodulator gauges width i.e. amount of signal passed through the system. Millivolt recorder can be calibrated to display the temperature. The lamp current could be used in other subsequent circuits as measure of temperature.

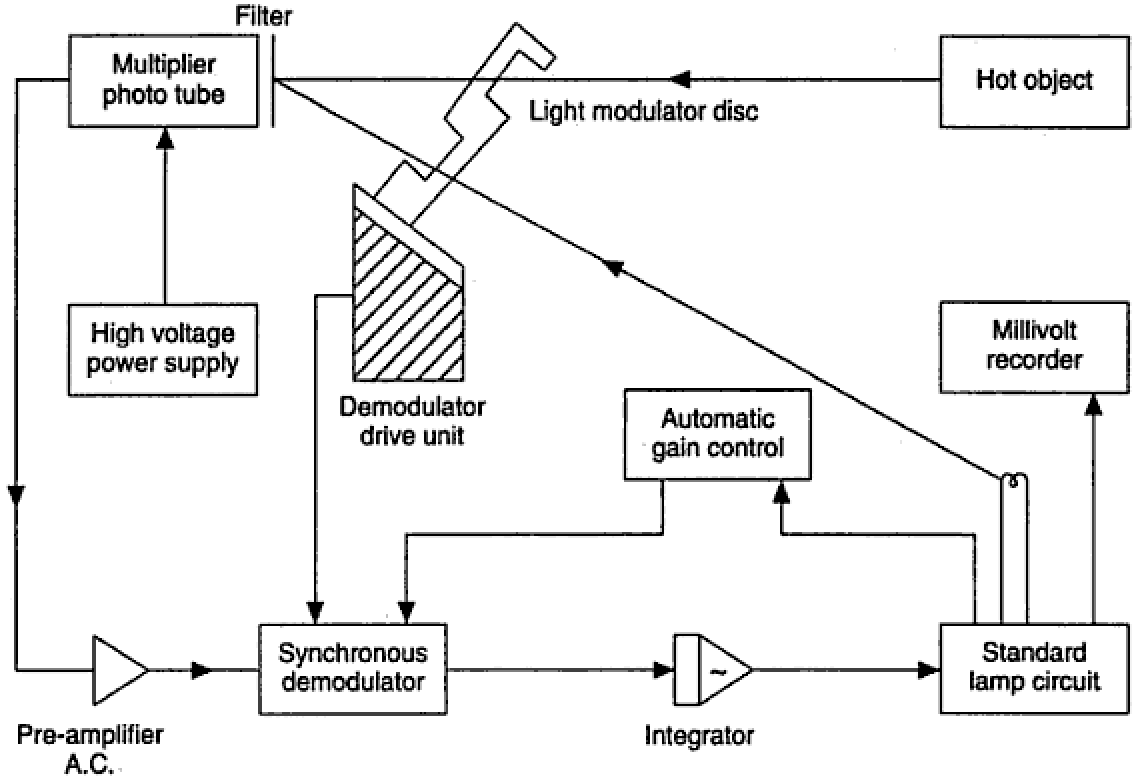


Fig. 2.23 Operational diagram of automatic optical pyrometer.

2.8.7 Silicon Temperature Transducers

Over the past few years, the increasing use of integrated circuits in control systems has stimulated a demand for electronics temperature sensor that is both accurate and reliable. Silicon temperature sensors are well placed to meet this demand. These sensors make use of temperature dependence of resistivity exhibited by silicon. Figure 2.24 shows this dependence for *n* and *p* type silicon at several doping levels *N*. The initial rise in resistivity is caused by the fall in free charge carrier mobility with rising temperature, and over this region, silicon exhibits a positive temperature coefficient of resistance. At higher temperature, when intrinsic semiconductor properties of silicon predominate, the mobility increases and resistivity falls.

Silicon diode temperature sensors have been developed by many semiconductor companies. In these devices, the base emitter voltage of a forward biased diode changes with temperature. These are low cost devices offering high accuracy, stability and linearity, but suffer from the disadvantages of low output and limited upper temperature range. These devices do not make use of properties of silicon as such.

Analog devices offers two devices AD590 and AD592 series as silicon temperature transducers. AD590 offers linear current and output of 1 microampere (μa) per degree kelvin. It should be used in any temperature-sensing application below +150°C, in which conventional electrical temperature sensors are currently employed. In addition to temperature measurement, these sensors can be used in variety of other applications, like flow rate measurement, level detection of fluids, biasing proportional to absolute temperature etc. It is available in five models I,J,K,L and M and each model is available in TO 52 can or flat package. The AD590 is particularly

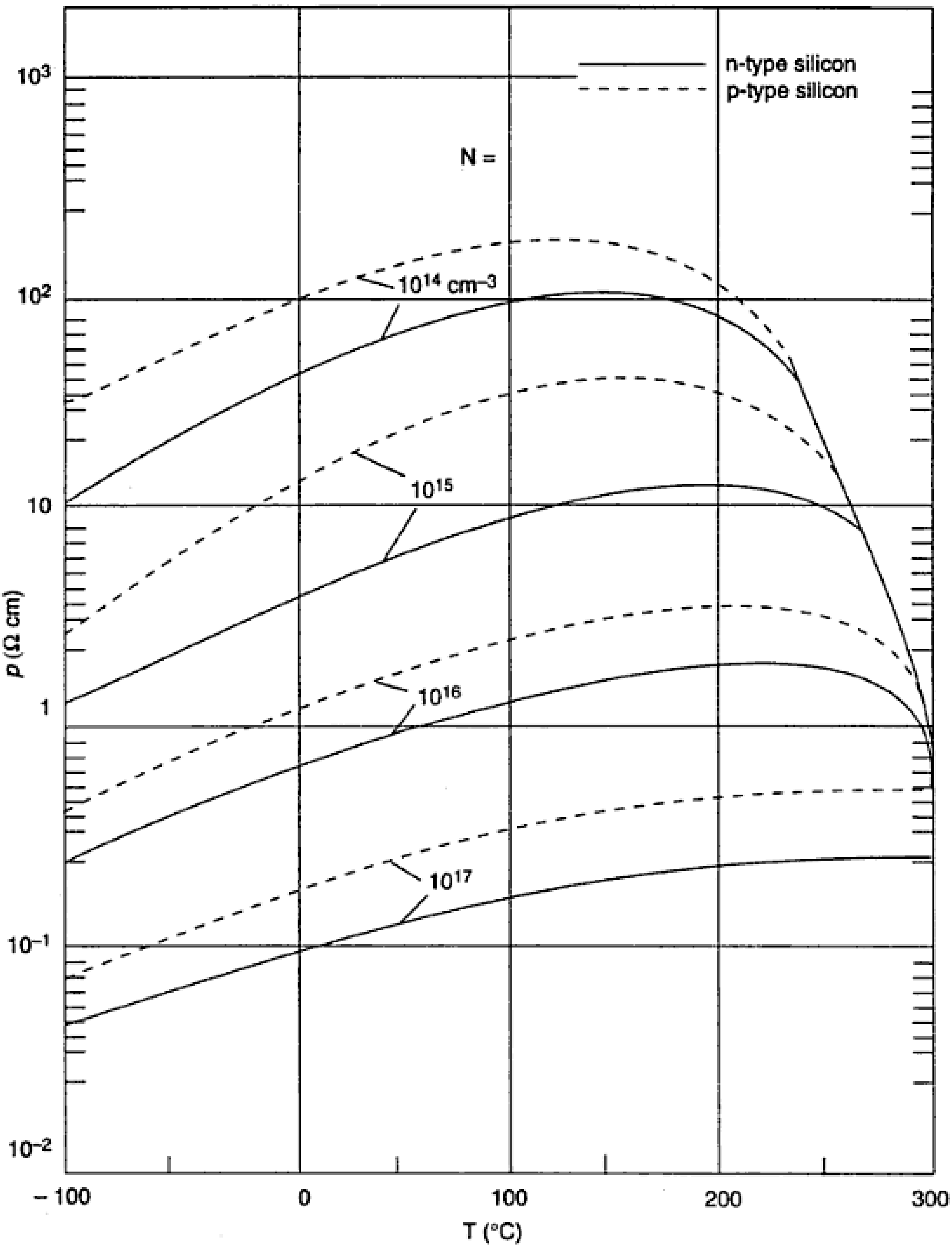


Fig. 2.24 Temperature vs. resistivity response curve for *p*- and *n*-type silicon.

useful in remote sensing applications. It is insensitive to voltage drops over long lines due to high impedance current output. Any well insulated twisted pair cable is sufficient for operation hundreds of feet from the receiving circuitry.

The AD592 is available in three performance grades AD592AN, AD592BN and AD592 CN. All the devices are packaged in a plastic TO 92 case. The device operating temperature range is from 25 to +105°C. It offers excellent linearity and output as micro amp. per degree K. Typical application areas include; appliance temperature sensing, industrial temperature control, automatic temperature measurement and control etc. Like AD 590, it is also well suited for remote sensing applications.

National Semiconductor has introduced LM 34, LM 35, LM 134, LM 135 and LM 3911 series of silicon temperature sensors, for different range and accuracy. LM 34 series is calibrated directly in degrees F, with temperature range of –45 to +150°C. Other series are calibrated in degree centigrade with temperature range of –55 to +150°C. These are available in TO 92 or TO 46 package and do not require any external calibration. LM 3911 is basically a temperature controller (range, –25 to +85°C). It includes a temperature sensor, a stable voltage reference and an operational amplifier (op. amp.) on the same chip. The op.amp. can be used as comparator to switch on the output as temperature sensed crosses the set-point. This makes the device suitable for on-off temperature control.

Philips has developed KTY81/83/84 series of planar silicon temperature sensors. The devices are manufactured, using the reliable planar technique. A layer of silicon nitride is used to protect the crystal surface and to provide additional protection, the entire crystal is coated with phosphor glass. Where KTY 81 and 83 can be used to measure temperature from 55 to 150°C, KTY 84 offers temperature range from 65 to 300°C. KTY 81 is available in SOD 70 type encapsulation while KTY 83 and 84 are available in SOD 58 type encapsulation. These devices can be operated with a constant voltage source or constant current source and linearization can be easily achieved in both cases.

Kulite has developed a unique sensor ITQ 1000, which offers integrated temperature and pressure measurement. The temperature within range 25 to +125°C and pressure within range 20 to 500 psi can be measured using this sensor. Its STQ and STH series of diffused silicon temperature sensors offer a wide operating range of –46 to 177°C.

Motorola offers MTS 102, 103 and 105 series of silicon sensors in TO 92 cases for –40 to +150°C. Intersil had similarly announced ICL 8073 and ICL 8074 temperature transducers in TO 52 cans over operating range –55 to +125°C.

2.8.8 Fibre-optic Temperature Transducers

Displacement sensors can be made to measure the temperature by using thermoexpansion or temperature-sensitive bimetal. The bimetal displacement caused by the temperature, generates misalignment between a pair of fibre lens connector assembly. This varies the amount of light arriving at the output end which is measured.

Temperature-sensitive transparent substances like liquid crystals and semiconductors are proposed to be used by Rockwell International Corporation as attenuator for temperature measurement, using optical fibres. Variation in temperature results, in colour changes in liquid crystals and band gap shifts in semiconductors. Thus, the amount of attenuation will depend on the temperature.

Rockwell International Corporation, USA, has also proposed a bi-fringent digital sensor which uses crystal polarization solution with temperature. Another approach being investigated is the use of a miniature optical Fabryperot resonator cavity at the tip of an optical fibre. The change in temperature causes variation in cavity length, resulting in changes in the fibre-end surface reflectivity which can be used to measure the temperature. Holographic processing of light information is also being developed at Rockwell International corporation.

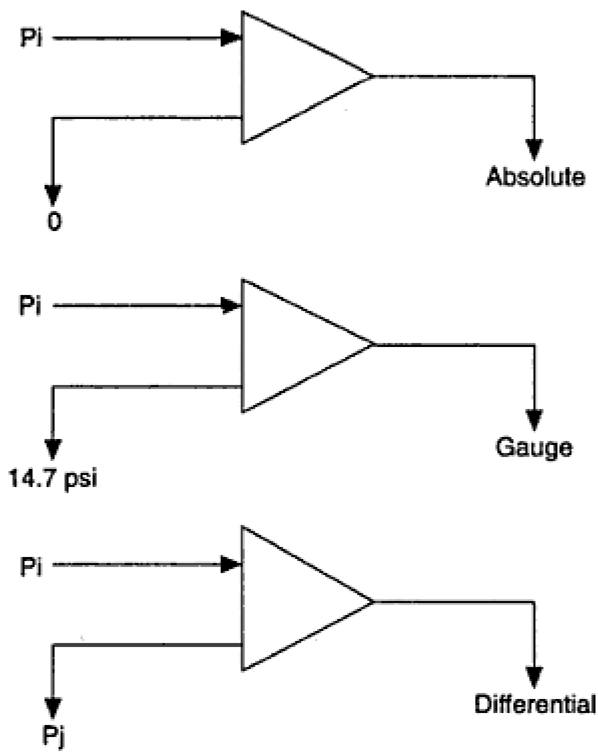
TRW (Technology Research Centre), USA, has developed a spectral temperature sensor. It is based on black body radiation of the heated fibre tip. A photodetector is used remotely to measure the optical power and thus temperature.

2.9 PRESSURE TRANSDUCERS

Pressure is very important parameter for any process. In various units of a plant, very high or very low pressure both may cause problems and may lead to partial or complete failure in operation. Let us discuss some nomenclatures before going into actual measuring systems.

Absolute pressure is the force exerted by the fluid per unit area of the wall of the container. It is represented in psia (pound per square inch absolute) in FPS unit. *Gauge pressure* is the difference between the absolute and the local atmospheric pressure (14.7 psi). It is normally expressed in psig (pound per square inch gauge) in FPS unit. When gauge pressure is negative, it is called vacuum. *Differential pressure* is a measure of pressure difference between both sides of transducer thin structure with both sides exposed to a different pressure level. It is expressed in psid (pound per square inch differential in FPS unit).

Symbolically these may be represented as follows:



The mechanical type pressure transducers include Bourdon tubes, Bellows, and Diaphragm gauges. Where bellows and diaphragm gauges are suitable up to about 4000 to 8000 psi, the Bourdon tubes are useful for high ranges.

The electrical methods of pressure measurement can be divided into two categories: *primary* and *secondary*. The secondary methods use a capacitive or inductive sensor (capacitance gauge, LVDT etc.), to convert displacement caused by bourdon tube, diaphragm etc. The primary pressure transducers use electrical methods and include piezoresistive (strain gauges), piezoelectric (quartz crystal) etc. The capacitive and inductive type secondary sensors have already been described under displacement transducers. We shall discuss here piezoelectric, piezoresistive, silicon and fibre-optic pressure transducers.

2.9.1 Piezoelectric Transducers

A class of solid polycrystalline dielectric materials when deformed by the application of force generate electric charges and vice versa. This is known as *piezoelectric effect.*

The charge produced due to the deformation by the application of pressure can be measured by a pair of electrodes mounted suitably. Natural crystals like quartz, Rochelle salt and synthetic materials like lithium sulphate, ammonia dihydrogen phosphate etc. exhibit the piezoelectric phenomenon.

The piezoelectric transducer is cut from a larger crystal in the direction of any of the electrical or mechanical axis, perpendicular to optical or crystal axis. The electrical axis (3 sets) is known as X axis and the mechanical axis as Y axis (Fig. 2.25).

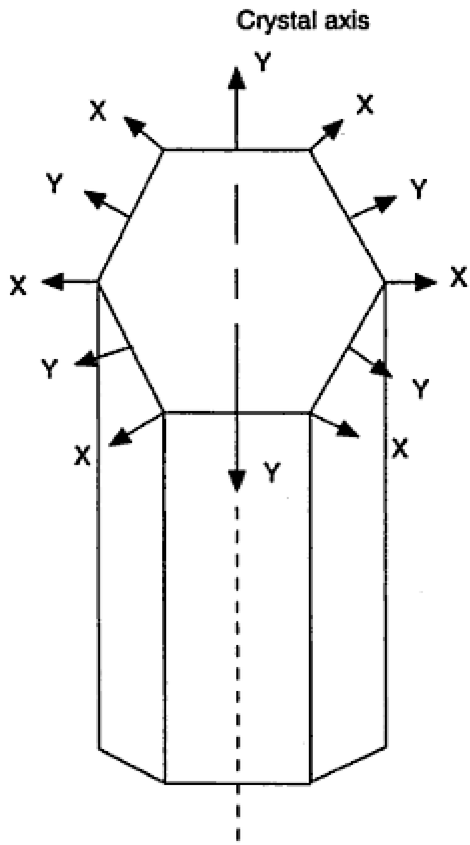


Fig. 2.25 A piezoelectric transducer cut from a larger crystal with electrical axis (X) and mechanical axis (Y).

The pressure measurement using a piezoelectric crystal is shown in Fig. 2.26. Let, F be the force applied in the direction of Z, resulting in total charges Q and output voltage e then,

Pressure (p) = force/area = F/area of crystal
Charge sensitivity (d) = charges per unit force generated = Q/F
Voltage sensitivity (g) = field produced per unit stress = $(e/t)/p$

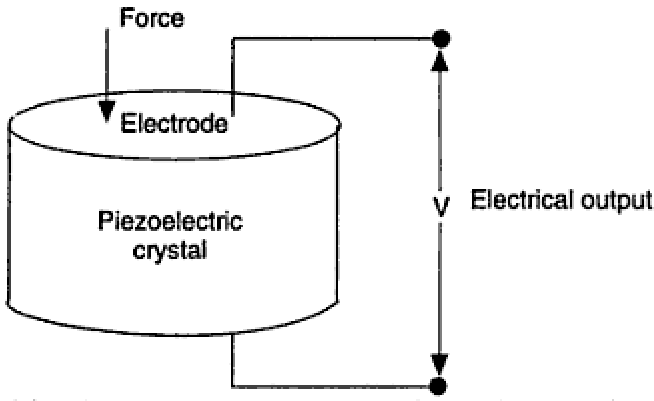


Fig. 2.26 The pressure measurement using a piezoelectric crystal.

We, therefore deduce that output voltage $e = pgt$, where, t = thickness of transducers. Thus, output voltage is linear function of pressure applied to the crystal.

The natural crystals are preferred as compared to synthetic crystals. This is because they show higher degree of thermal and mechanical stability, can sustain higher stress, have low leakage and exhibit good frequency response. Only barium titanate, out of synthetic crystals shows these characteristics.

Some piezoelectric transducers are designed as resonant types. In this case, the crystal is driven at resonance from a suitable oscillator and the voltage required to achieve this is measured. The application of pressure changes the resonance frequency and the voltage required to achieve the resonance. The change in voltage is measured to determine the stress.

2.9.2 Piezoresistive Transducers

When a wire is stretched within the elastic limit, it will have an increase in length and corresponding decrease in diameter. Thus resistance of wire changes due to the strain. This is called *piezoresistive effect.*

If ΔL be the increase in length and ΔR be the increase in resistance then,

$$\Delta R/R = K \cdot \Delta L/L = K \cdot \sigma/E$$

where

R = original resistance,
L = original length,
E = Young's modules of elasticity,
σ = stress = force/area

The value of K varies between 2 and 6 for metals and for semiconductor materials values up to and above 180 are obtained.

The strain measuring circuit consists of a bridge as shown in Fig. 2.27. One arm of the bridge contains the strain gauge, while other arms have standard resistor of equal resistances, as

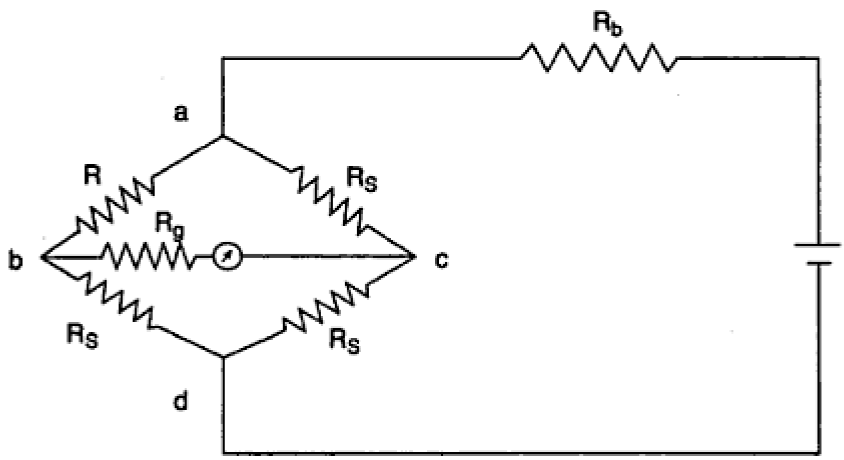


Fig. 2.27 An illustration of a strain measuring circuit.

that of gauge resistance in the unstrained condition. The current through the bridge arm measures the strain.

The construction of strain gauge is shown in Fig. 2.28. It consists of a measuring element embedded in a carrier material for better handling. Electrical connection is realized via external electrodes. According to the relevant manufacturing processes, four major strain gauge types are distinguished: Flat strain gauges, Wrapped around strain gauges, Foil strain gauges, and Semiconductor strain gauges (Fig. 2.29).

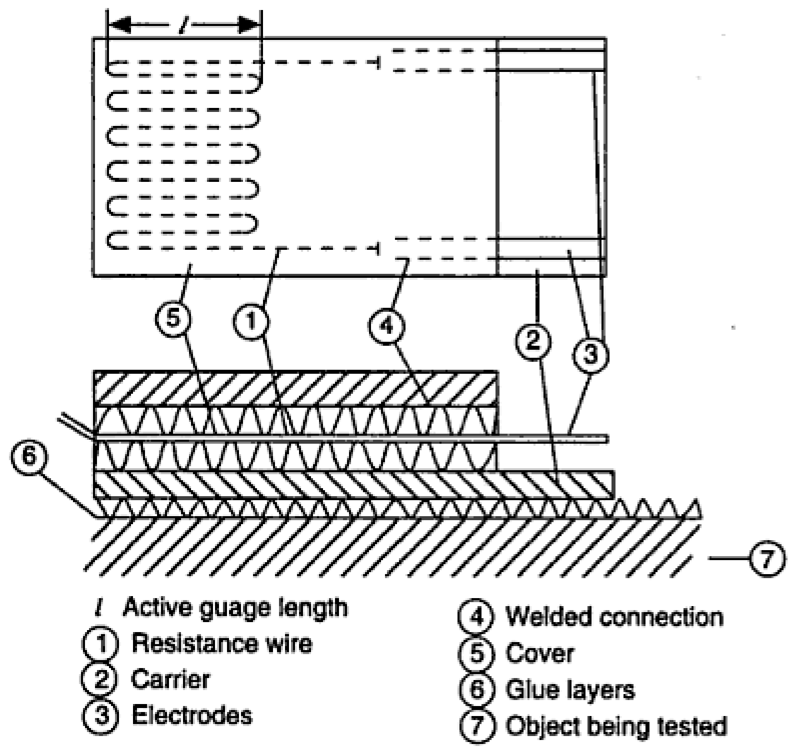


Fig. 2.28 Construction of a strain gauge.

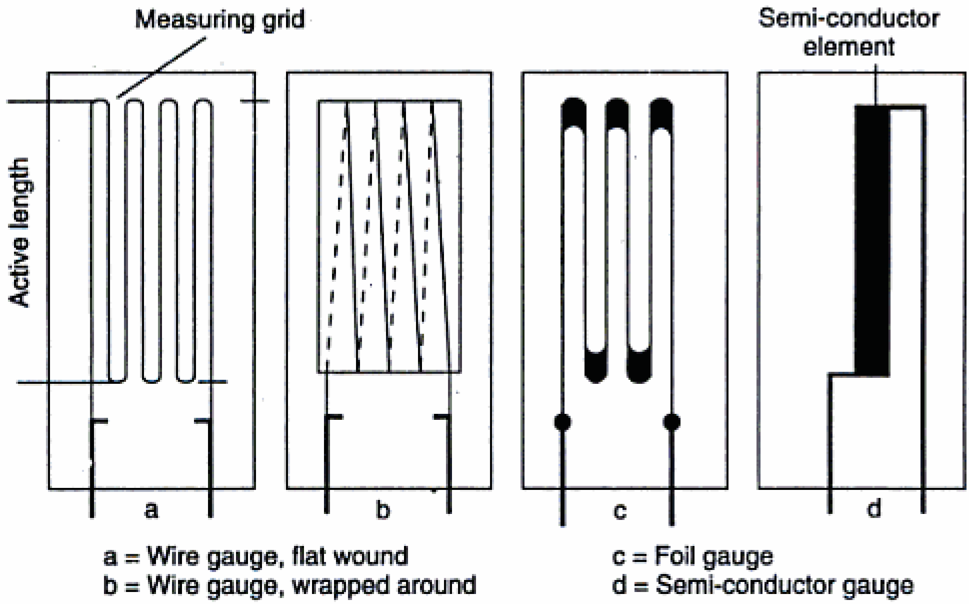


Fig. 2.29 Types of strain gauges.

Wire strain gauges are made of constantan (60% Cu, 40% Ni alloy) wire of about 20 to 30 μm diameter, wound flat or around a piece of carrier material. The foil strain gauge consists of a rolled constantan foil of 2 of 10 μm thickness. The measuring grid is produced by etching, after application of carrier.

The types of strain gauges mentioned may be put in several arrangements. The most commonly used are linear gauges used for measuring material strain in a known direction. In case the main direction of strain is unknown, rosette gauges are used. These consist of several measuring grids arranged on a common carrier (Fig. 2.30).

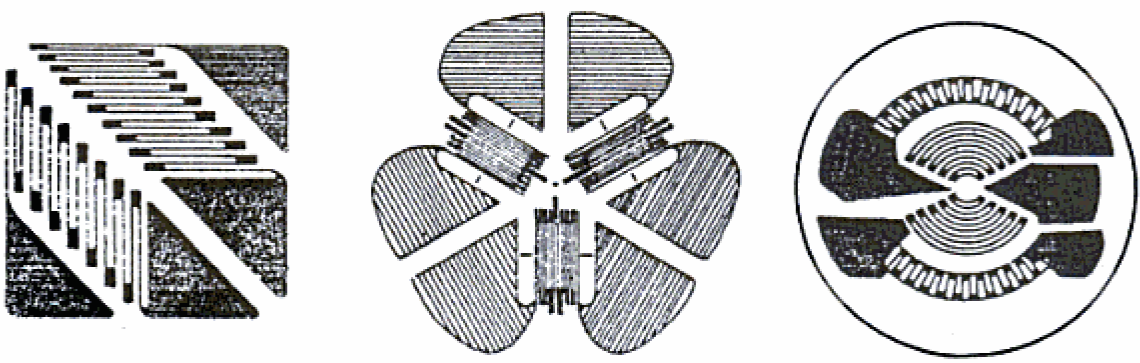


Fig. 2.30 Various measuring grids arranged in a common carrier.

2.9.3 Bridgeman Resistive Transducer

When a wire is subjected to pressure from all sides, its electrical resistance changes due to distortion produced in the crystal lattice. In most common metal wires the pressure causes the decrease in resistance, where antimony, bismuth, lithium, maganin show the increase in resistance with pressure as shown in Fig. 2.31. In cesium it initially decreases for small values of pressure changes and reaches a minimum, beyond which it increases with increase of pressure. The relation can be approximated by equation,

$$R_p = R_0 (1 + \beta \Delta P)$$

where

β = pressure coefficient of resistance,
R_0 = resistance at standard atmospheric condition,
ΔP = pressure difference applied,
R_p = resistance when pressure is applied

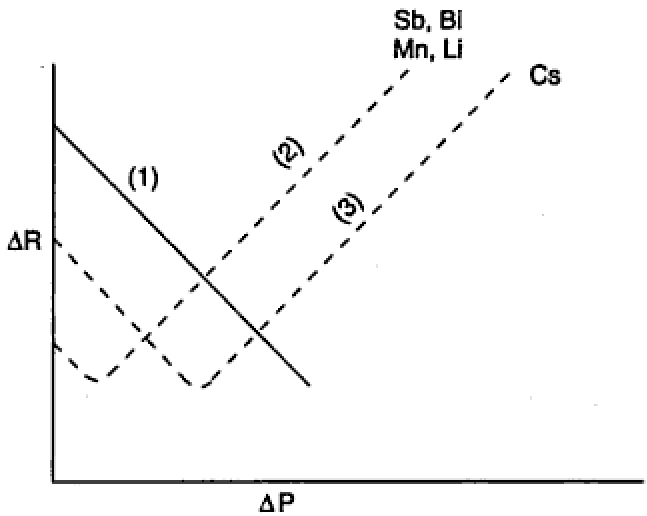


Fig. 2.31 Pressure-resistance characteristics of Bridgeman transducers.

The value of β is quite large for alkyl metals, antimony and bismuth but these materials are not convenient for practical realization of Bridgeman gauge. The construction of Bridgeman gauge is shown in Fig. 2.32. It consists of a bone ring of about 1 cm diameter and 0.5 cm thickness, wound with a 38 gauge insulated maganin wire ($\beta = +2.3 \times 10^{-6}$ cm^2/kg) to have a total resistance of 100 ohms.

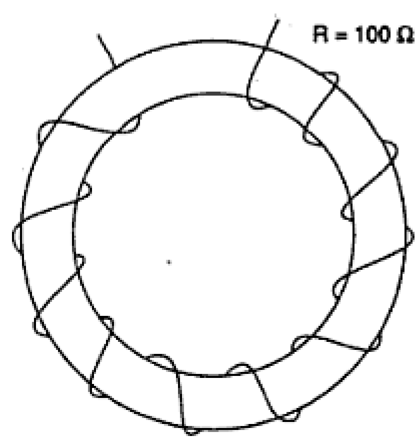


Fig. 2.32 Construction of a Bridgeman gauge.

2.9.4 Silicon Pressure Transducers

Piezoresistive integrated sensor technology is today's emergent transducer technology. Silicon is very responsive to strain with K factors of –100 to +180. The silicon pressure transducers incorporate a diffused four-arm wheatstone bridge on the surface of silicon diaphragm. Of particular note is the high natural frequency, low hysteresis and super thermal and environmental performance. Though originally silicon was adopted because of its large piezoresistive coefficient and compatibility with transistor fabrication techniques, it has now been found to possess excellent, transducer characteristic as well.

Figure 2.33 shows a thin diaphragm piezoresistive pressure sensor using integrated circuit technology. The top view, cross-section and enlarged details are shown in Fig. 2.33(a), (b) and (c) respectively.

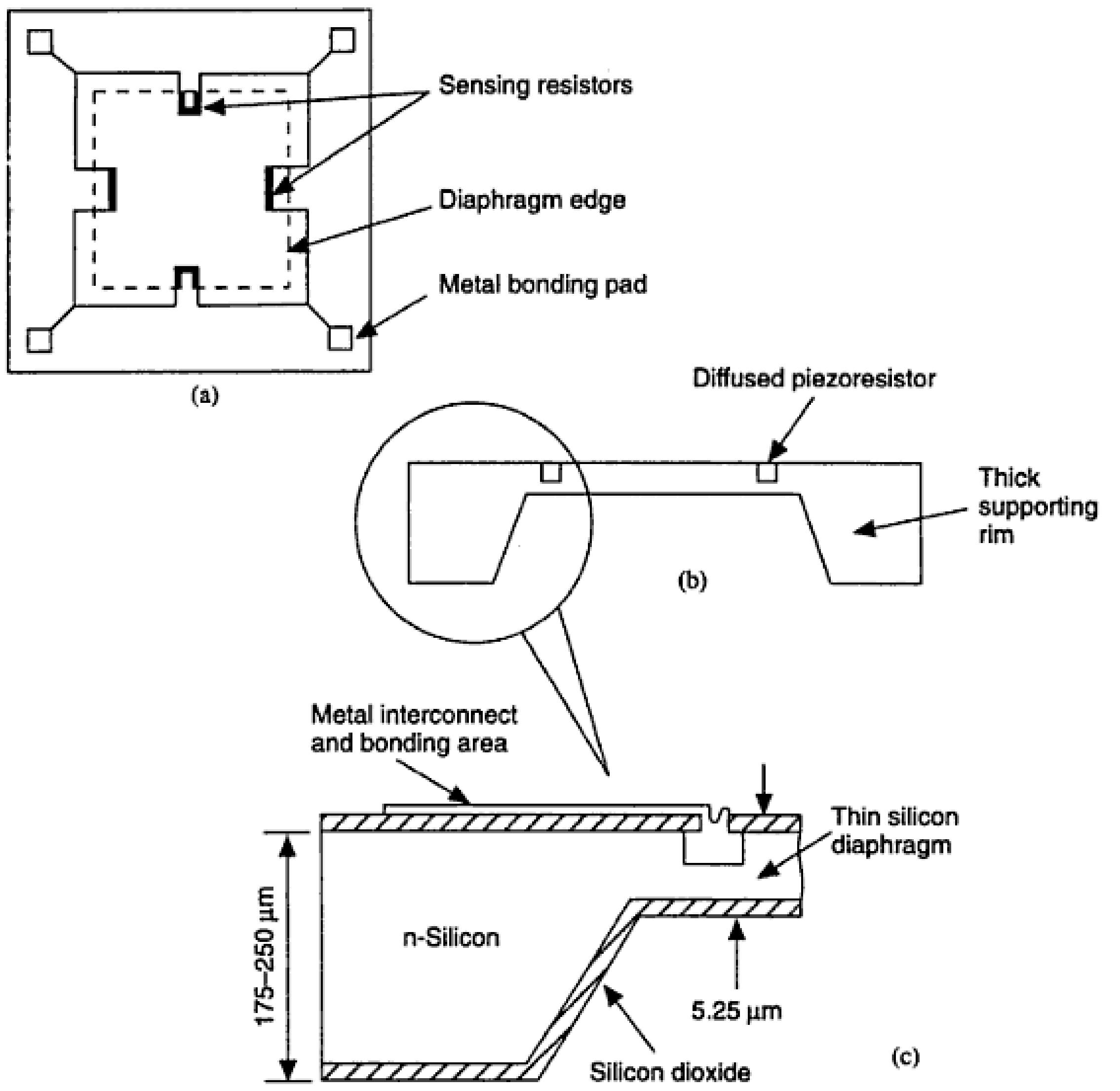


Fig. 2.33 Silicon piezoresistive pressure sensor: (a) Top view, (b) Cross section, and (c) Enlarged detail.

Figure 2.34 shows the action of sensor chip when pressure is applied. Due to pressure, the resistance of diffused bridge resistors changes and output is generated.

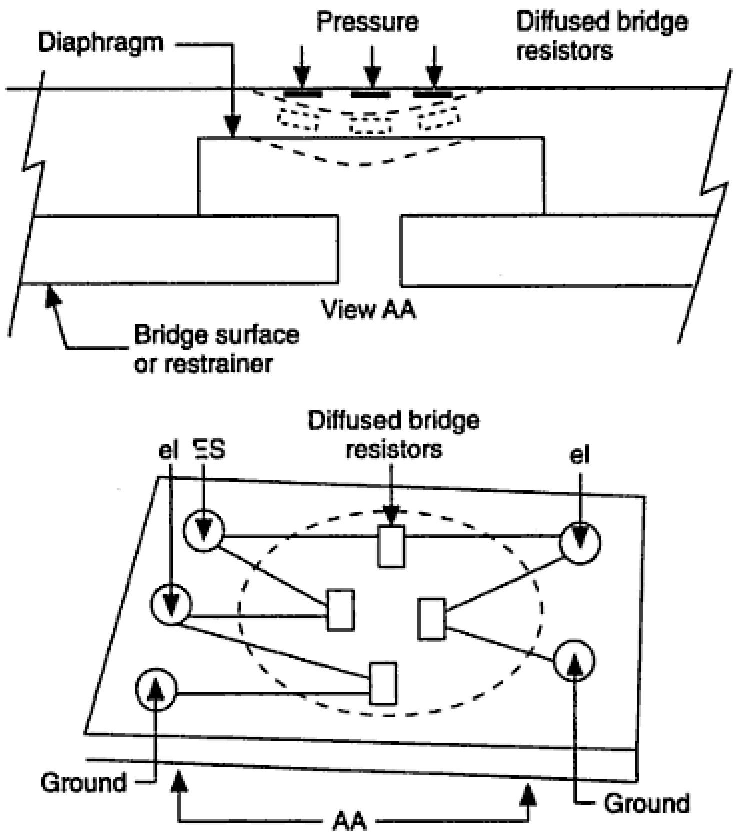


Fig. 2.34 Illustration of sensor chip action.

IC Sensors USA has developed C series of Piezoresistive silicon sensors. The models 10, 20, 30, 40, 12, 22, 32, 42, 13, 23, 33, 43, 80, 90, 103, 104, 105, 113, 114, 115, 210, 300, 310, 410, 419, 1210/1220, 1219/1229 and 1419/1429 offer different ranges of pressure measurement from 0–2 psi to 0–5000 psi differential, gauge or absolute. Out of these, there are some models specially suited for use with corrosive or conductive fluid or gaseous media. In some models (12, 22, 32, 42) integral temperature compensation is provided, whereas in others the temperature compensation is accomplished with the addition of three resistors whose values are specified.

In 1959, Kulite Semiconductor Products Inc. began producing first bulk silicon and later diffused silicon pressure sensors for military and aerospace need. Kulite now produces a wide range of silicon pressure transducers. CQ-030,CQ-080 series transducer are perhaps the smallest transducers in existence today. The diaphragm diameter ranges from 0.030 inch to 0.080 inch. The measuring pressure ranges from 0–5 psi to 0–500 psi.

Kulite produces various series of pressure transducers like XT, XTE, XST, XCQ, XCS, HKS, ETM, LQ, IPT, VM, BM, PTQS, PTQH and ETQ. Each series has different applications and pressure range. As an example IPT750 and BM 5750 are flush metal diaphragm pressure transducers suitable for measurement of liquid level in tanks (range 0–5 psi to 0–1000 psi) used in food and brewing industries. IPT-1100, BM-1100 and BME1100 series are standard metal diaphragm pressure transducers with integral inlet and port adapter. It can be used in a number of applications including hydraulic and pneumatic pressure measurement. Versions with integral amplifier with an output of 5 volt are also there. The measuring range varies from 0–5 psi to 0–10000 psi.

The Philips also manufactures pressure transducers, of various ranges. KPZ 10G and KPZ 11G use a thin film polycrystalline resistor layer mounted on one side of the metal membrane to translate direct pressures into changes of resistance. Reference pressures of –1 to +2 bar (KPZ 10G) or –1 to +10 bar (KPZ 11G) can be measured. A 6-pin package encapsulates the composite metal and thin film membrane. There is provision for an IC to give temperature compensation, data processing and offset voltage trim. Since they provide direct contact on the metal side of the membrane, these sensors are suited for harsh environments which require direct contact with the fluid being measured, such as oil or hydraulic pressure monitoring in automobiles.

The KEZ 10 (0 to 10 Newton) and KEZ 11 (0 to 30 Newton) use a similar technology but measure strain. Main application will be in weighing equipment as well as other equipment requiring force measurements. These sensors can also be used to measure extremely small displacements (20 to 50 μm max).

KP 100A is another pressure sensor, manufactured by Philips. It measures absolute pressure up to 2 bar in clean-air or inert media environments. Using a monolithic silicon membrane with diffused resistors, the sensor incorporates its own temperature compensation circuit. The complete sensor is encapsulated in a 6-pin DIL package for direct PC board mounting. One side of the membrane is left to the atmosphere or other inert media which in turn imposes pressure on the membrane thus, causing a change in resistance of the diffused resistors.

Conrac Corporation System West division has designed a silicon on sapphire (SOS) transducer for pressure measurement. It is a high temperature, high accuracy sensor in which a silicon piezoresistive strain gauge is grown epitaxially on a sapphire diaphragm, as shown in Fig. 2.35. The series 4720 transducer can handle up to 1000 psi absolute pressure. The monolithic construction imparts a high degree of insensitivity to shock and vibration. Also strength to weight ratio of

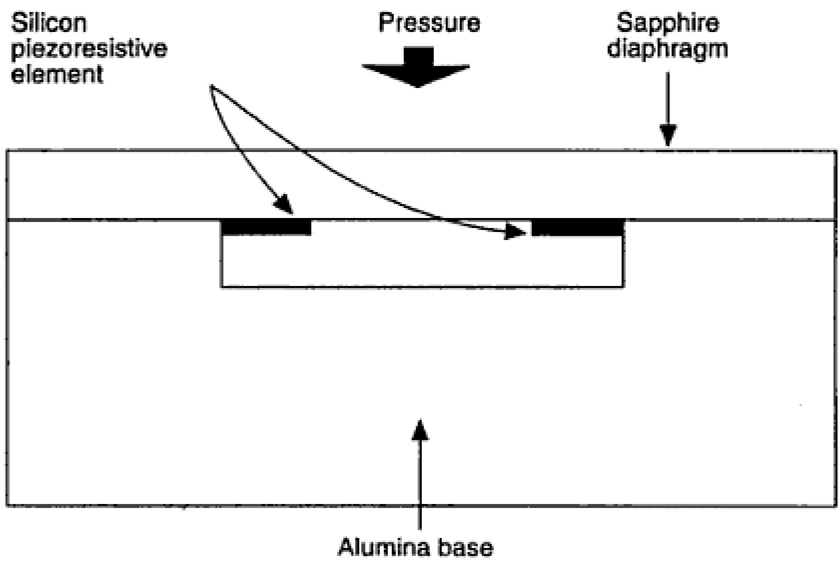


Fig. 2.35 High performance pressure transducer using silicon on sapphire technology.

sapphire is twice that of steel. This also reduces the error due to vibration and shock. The design is aimed to achieve longer transducer life. However, the superior performance of the transducer adds to their cost.

A pressure sensor from Nova Sensor, USA incorporates Silicon on Insulation (SOI) technology to operate in high temperatures. The initially offered pressure range for Novapix sensor is 0 to 100 psi. The sensor uses a proprietary wafer lamination technique to form piezoresistive elements integral to silicon diaphragm. The operating temperature range is 0 to 250° C.

Foxboro/ICT produces a silicon pressure transducer which ranges from TO.8 PCB mountable sensors to hazardous area rated pressure transmitters. The silicon sensor is protected by a steel diaphragm which is welded to the pressure connection for NEMA-4 sealing.

To reduce the cost of pressure transducers, Motorola has adopted a totally new approach for pressure measurement through piezoresistor method. Instead of opting for conventional Wheatstone bridge circuit, Motorola used a single P-type cross shaped silicon element, as shown in Fig. 2.36. Because of the shape the transducer is called X-ducer. A constant current passes

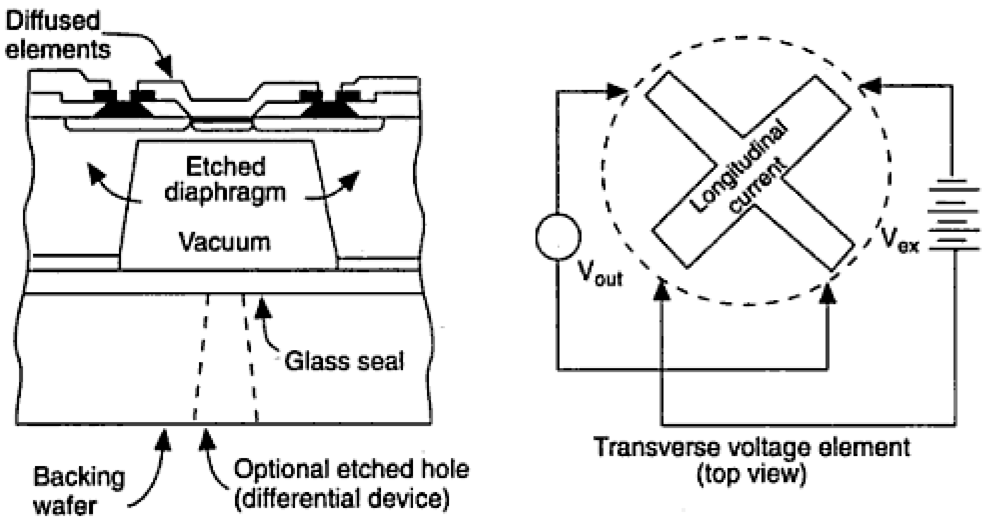


Fig. 2.36 Motorola's X-ducer for pressure measurement.

through the longitudinal axis of elements thus generating a transverse voltage across the latitudinal axis. When pressure is applied this output voltage changes. The sensor is available in simple plastic package which further reduces its cost. A pressure range of 1 to 40 psi (differential and absolute) can be handled.

Monolithic Sensors Inc. has developed a capacitance based silicon pressure sensor which can be used for low pressure measurement, has high thermal stability and high strength. Since their introduction in 1980s, the silicon pressure transducers have undergone considerable improvement.

2.9.5 Fibre-Optic Pressure Transducers

Dressner Industries, USA have brought out a pressure sensing device which uses movement of a diaphragm to amplitude modulate a light source.

Sperry Research Centre and TRW, USA have developed a photoelastic fibre-optic sensor for pressure measurement. The propagation modes in fibres possess polarization properties. These properties depend on the relationship between some preferred direction in the fibre and electric and magnetic field directions of the light waves. In fact, the light emerging from a multimode optical fibre of sufficient distance contains a large number of spatial and temporal modes whose intensities are equally divided into the two orthogonal polarization states.

The scheme developed uses a pair of optical polarizers as light valve to rotate the plane polarized light or to change the plane of polarization. As shown in Fig. 2.37, the first polarizer

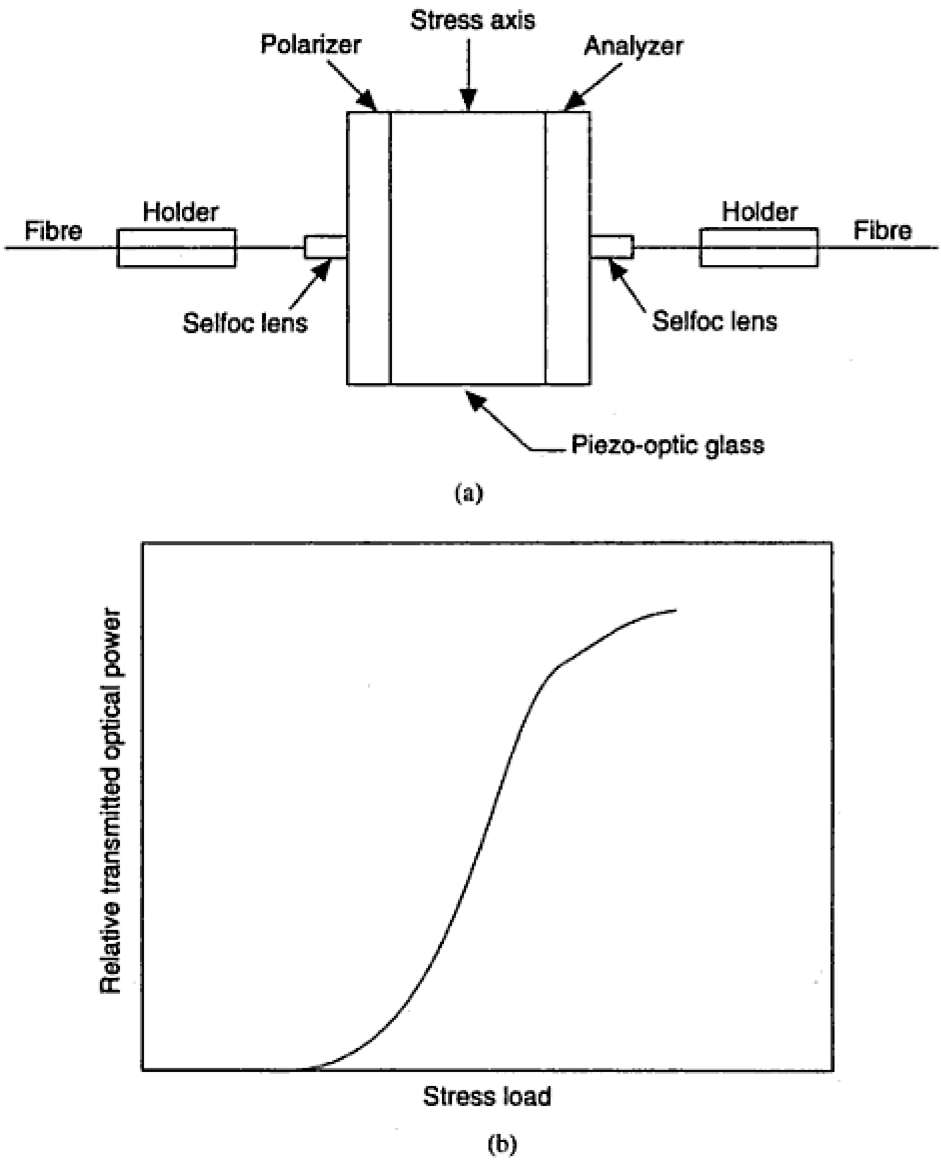


Fig. 2.37 The photoelastic fibre-optic pressure sensor: (a) Device configuration, and (b) Pressure sensor response obtained at TRW.

allows half the optical power to enter the glass block with well defined polarization status. The second polarizer is located behind the glass box. It is aligned in the cross state relative to the first polarizer. Thus in normal situation, resultant light at the output optical fibre will be nil. When pressure is applied to glass block, the polarization is changed by photoelastic effect; resulting in light in output fibre.

The Fabryperot resonator cavity (discussed in Fibre-optic Temperature Transducers) made at tip of optical fibre suffers changes in length due to pressure also. A pressure sensor can also be designed using this approach.

2.10 LIQUID LEVEL TRANSDUCERS

The level sensing methods include the use of fluid pressure sensor, float, capacitive or conductive methods. Using these methods, the level of any liquid in a tank or any other container can be measured.

2.10.1 Fluid Pressure Transducers

The schematic of fluid pressure transducers is shown in Fig. 2.38. Any of the fluid pressure sensors like bellows, bourdon tube, diaphragm sensors, can be used at the bottom of tank. The fluid pressure is directly proportional to the level of liquid in the tank.

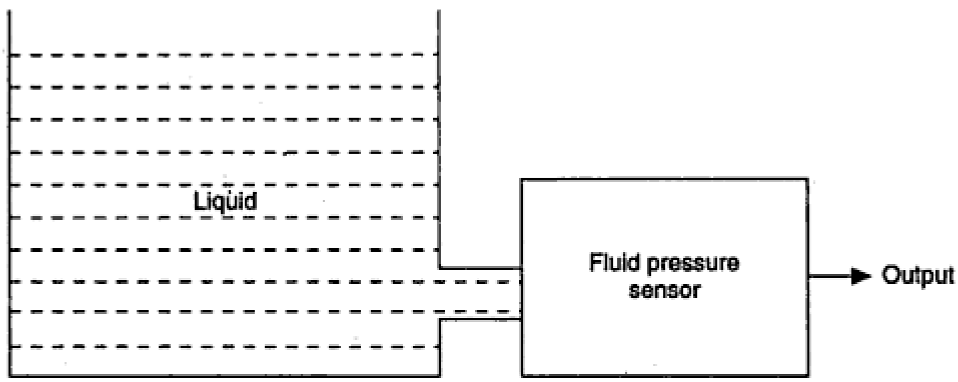


Fig. 2.38 The schematic of fluid pressure transducers.

2.10.2 Float

It is the most common liquid level sensor. The float is made of hollow metal or plastic ball, which will always remain at the level of liquid. The float is operated with potentiometer. The other end of float is connected to movable arm of potentiometer as shown in Fig. 2.39. As the liquid level varies, the float goes up or comes down and this operates the movable arm of potentiometer. The change in resistance is directly proportional to the change in liquid level.

2.10.3 Capacitive Transducers

The capacitive liquid level sensor is used in case of non-conductive liquids. If the tank containing the liquid is made of metal (Fig. 2.40), one insulated metal electrode is inserted in the tank, and variation of capacitance between electrode and tank wall with liquid level is measured. The liquid forms the dielectric medium between the two parallel plates. As the liquid level varies, the capacitance also varies. If the tank is not made of metal then two electrodes are used and variation of capacitance between them is measured. The capacitance output is proportional to the liquid level.

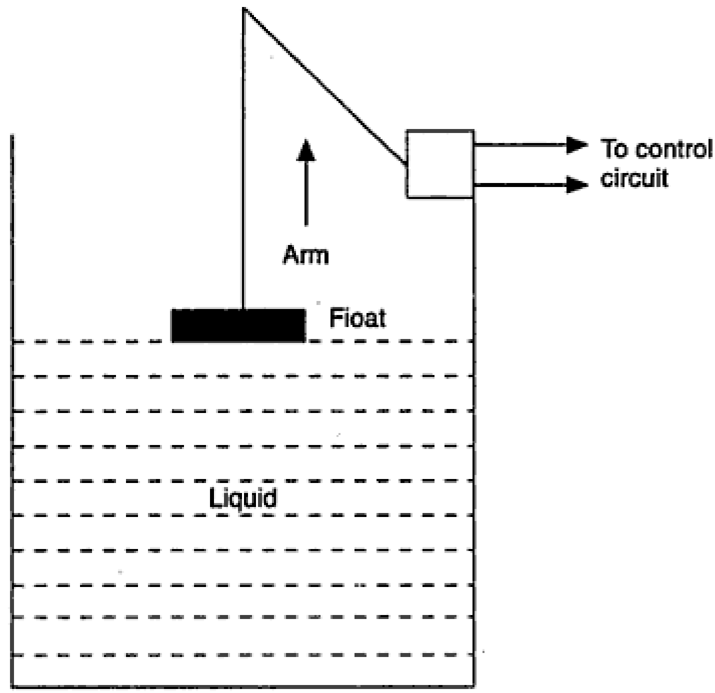


Fig. 2.39 Float as liquid level sensor.

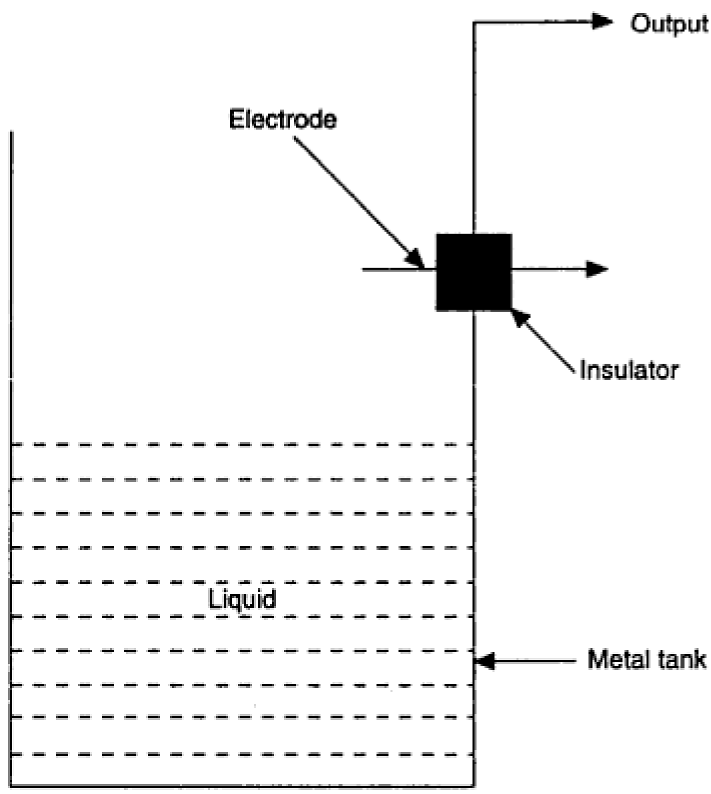


Fig. 2.40 Capacitive transducer (in case of non-conductive liquids).

2.10.4 Conductive Transducers

If the liquid is conductive (Fig. 2.41) then we measure the change in resistance between two electrodes or one electrode and container wall. The current flows through the liquid and as the liquid level varies the resistance also varies proportionally.

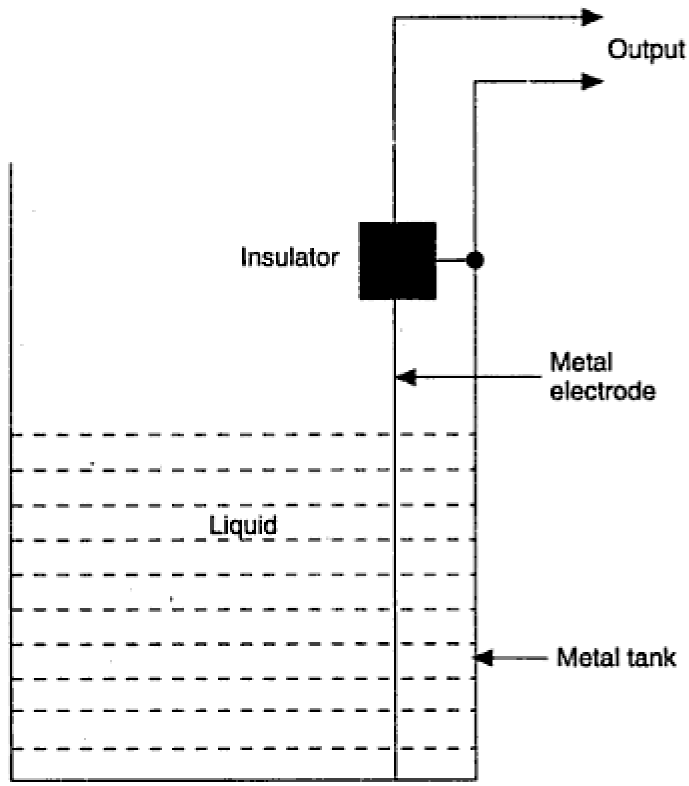


Fig. 2.41 Conductive transducer (in case of conductive liquids).

2.10.5 Limit Transducers

In many applications, it is only required to know when the liquid has reached a pre-defined level, so that any desired control action (closing or opening of valve) may be taken. Most common and simplest device is float switch. It is widely used in water tanks. The arm of the float is connected to a switch through a rod (Fig. 2.42). When float reaches a particular level, the switch is operated through the rod. When the level decreases, the float comes down and again the rod operates the switch in the opposite direction. An electrode can be set at the particular level in a metal container in case of a conductive liquid. When liquid touches the electrode, the circuit is completed (Fig. 2.43). In case of non-metal container, two electrodes are used as shown in Fig. 2.44.

2.10.6 Silicon Liquid Level Transducers

Texas Instruments Inc. USA has developed a sensing element ST 004, to sense the liquid level. A tiny silicon chip resides in the sensor with a level wire connected to either face. The ST 004 sensor fits into a probe ST 004-B which has holes through which liquid can enter. When liquid

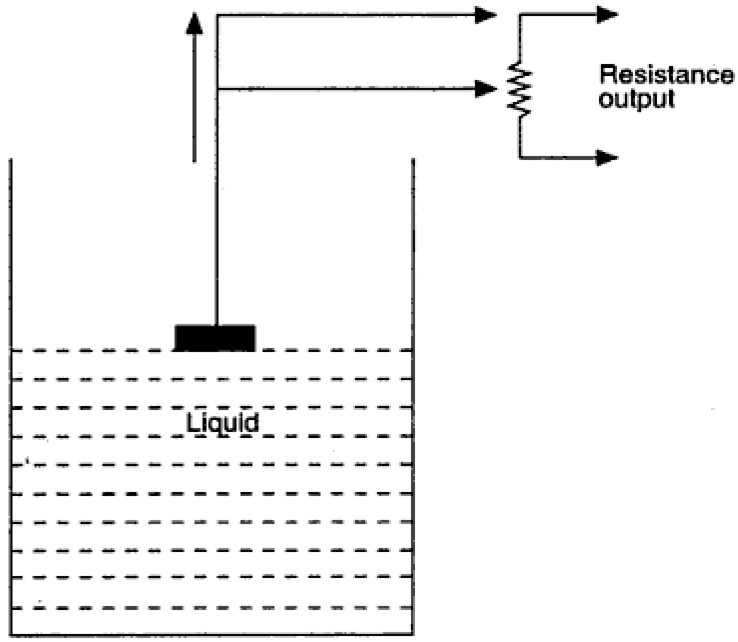


Fig. 2.42 Limit transducers.

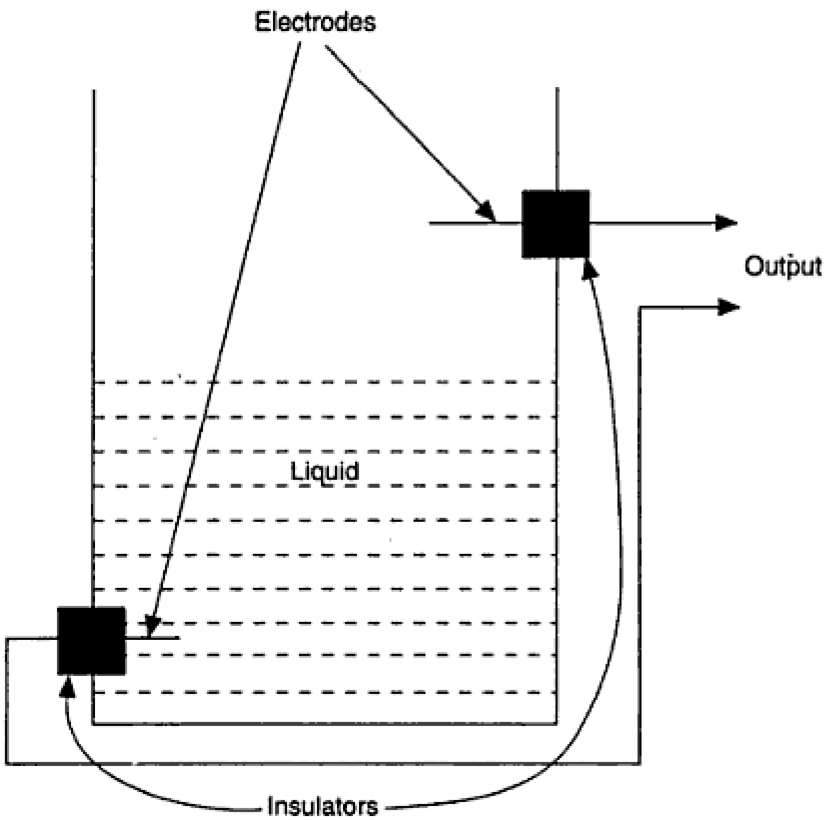


Fig. 2.43 Diagram illustrating completion of a circuit when conductive liquid touches the electrode.

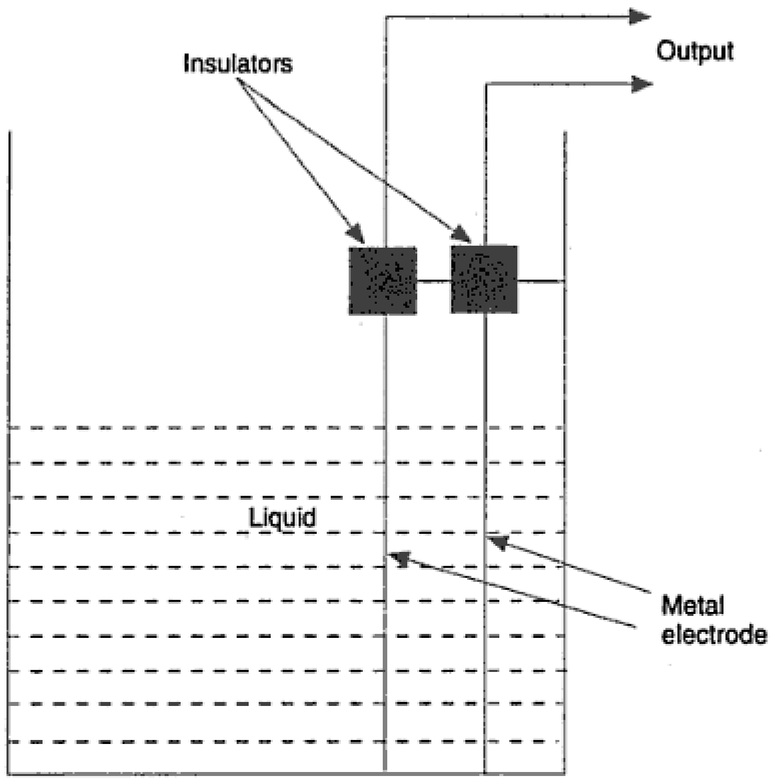


Fig. 2.44 Use of two metal electrodes in non-metal tank.

reaches the level of probe, it enters through the holes and comes in contact with sensor chip. This changes the temperature of the silicon chip and there by changes the current passing through the chips.

2.10.7 Fibre-optic Level Transducers

TRW and Lewis Engineering have developed an optical fibre sensor for liquid level, based on the principle of total internal reflection. The scheme is shown in Fig. 2.45. It contains an input fibre, an output fibre and glass reflective surface. The input and output fibres and reflective surface are arranged in such a manner as to provide total internal reflection when surrounded by air. When liquid touches the glass surface, the refractivity of surface changes, thus eliminating the total internal reflection. A signal can therefore, be generated when liquid reaches a particular level.

2.11 INTELLIGENT SENSORS

The advancements in microminiaturisation has resulted in combination of sensor and electronics in the same chip, thus leading to the integrated sensors or intelligent sensors. At the first step, hybrid units were developed which mounted one or more sensors, their interfaces and even microprocessor into a single package, resulting in the functional equivalent of an integrated circuit.

It is even possible to place sensors within sensors. Thus monitoring of internal temperature of sensor could be done by another internal sensor, and output of main sensor could be modified in order to compensate for known parameter changes with temperature. The output signal from sensor need not be continuous analog but may be converted to frequency, phase, pulse width as well as serial or parallel form by integrated processing power within sensor.

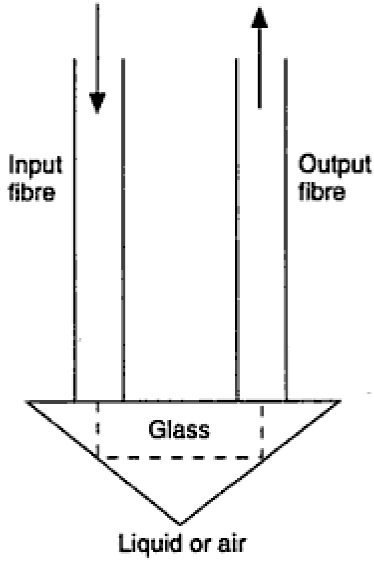


Fig. 2.45 Liquid level sensor based on total internal reflection.

2.11.1 Desirable On-chip Signal Processing

Following categories of on-chip signal processing have been identified for integration with silicon sensors:

(i) *Amplification.* The electrical output signal of sensor is weak, and therefore, not suitable for transmission. This can be amplified.

(ii) *Signal conditioning and formatting.* The output signal of sensor may be converted to digital for better noise immunity. The digital signal can then be encoded in several forms like serial, parallel, frequency, phase and pulse rate. The output format from sensors could also be standardised. Most have high internal impedance, which makes these susceptible to noise. On-chip impedance transformation could be achieved to solve this problem.

(iii) *Improvement in characteristics.* On-chip electronics could bring the following improvements in the characteristics of sensors:

(a) *Non-linearity.* Most sensors show some non-linearity. This could be improved using look up table or feedback system.

(b) *Cross sensitivity.* Most sensors show undesirable sensitivity to strain and temperature. These parameters can be measured by incorporating such sensor elements in the sensors. The effect could be compensated through on-chip electronics.

(c) *Frequency response.* The frequency response of sensor could be improved through proper feedback mechanism, using on-chip electronics.

(d) *Parameter drift.* The offset, sensitivity and linearity undergo change with time as component values change. Using on-chip accurate current and voltage sources, this problem could be overcome.

2.11.2 Present Status

The silicon pressure sensors have been in use for quite some time. A number of piezoresistive silicon transducers are available now with on-chip amplification and temperature compensation. A pressure sensor with frequency output has also been designed. Honeywell's Process Control Division has developed an intelligent pressure sensor that compensates for both temperature changes and offsets due to static pressure loading effects.

The Sharp Corporation has developed a combined humidity/temperature sensor on a single chip. It was difficult to combine humidity sensor with FET, since silicon transistor elements are sensitive to moisture. The problem has been solved by using humidity-resistant silicon nitride layer on the surface of the element, and a double gate electrode structure. The temperature sensing range is between –20 to +100°C with response time of 30 seconds. The humidity change from 0 to 100 per cent may be sensed with response time of 60 seconds or less.

A number of developments in intelligent sensors have been reported in the area of *tactile sensors* used in Robots. Tactile sensing is a continuous variable sensing of forces in an array and is meant to relate to skin-like properties where areas of force sensitive surfaces are capable of reporting graded signals and parallel pattern of touching. This is in contrast to simple touch, which is force sensing at a single-point or binary sensing at multiple sites. Since high level of integration and processing is basic requirement in robotics, the intelligent sensing efforts are directed towards robotic applications.

2.12 BIOSENSORS

The advent of biosensors have led to positive developments in the field of process control. The combination of electro-chemistry, biochemistry, physics and integrated circuit silicon technology has resulted in highly specific, sensitive, selective, accurate and reliable micro-biosensors. The application of biosensors are primarily in the following areas:

1. Robotics (sensing devices for automated machinery in hostile environment, vehicles, health care),
2. Environment (detection of toxic chemical in air, water and soil),
3. Industrial Control (water and waste monitoring, cosmetic testing, fermentation, food and drug processing),
4. Medical (drug testing, blood banks screening laboratories etc.),
5. Agricultural (diagnosis of plant and animal diseases, solid and water testing, BOD measurement, quality control of meat and plant products).

Currently, four general sensors technologies, viz., electronic, surface acoustics waves, optoelectronic and microchromotography are being investigated in different laboratories. Microelectronics biosensors, based on conductimeteric principle have been introduced and are giving good results.

2.12.1 Biosensor Technology

A *biosensor* is an analytical device which uses biologically sensitive material to detect biological or chemical species directly, without complex sample processing. Usually a biologically sensitive material is attached to a suitable transducing system which converts the biochemical response to a quantifiable electrical signal. The biologically sensitive material can be an enzyme, organelle, membrane component, bacterial cell, an antibody or an antigen. Figure 2.46 shows the configuration

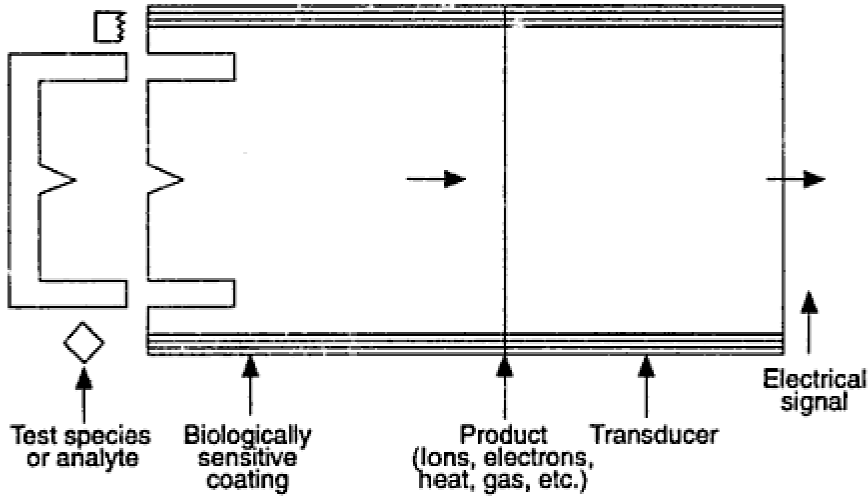


Fig. 2.46 Configuration of a generalised biosensor.

of a generalised biosensor. When biological molecules interact, this results in the change in one or more physico-chemical parameters associated with the interaction. This change may produce ions, electrons, gases, heat, mass or light. These quantities are converted into the electrical signal by transducers. The transducer signal may be *amplified, processed* and *displayed* in suitable form. Table 2.3 shows the types of the transducer measurement, and typical applications which have been exploited so far. The biosensors may be of the following types:

Table 2.3 Types of Transducers Exploited in Biosensors

Transducer system	Measurement mode	Typical applications
1. Electrochemical		
(a) Conductimetric	Conductance	Enzyme-catalysed reactions
(b) Enzyme electrode	Amperometric (current)	Enzyme substrates and immunological systems (antibody-antigen)
(c) Field effect transistors (FET)	Potentiometric (voltage)	Ions, gases, enzyme substrate and immunological analytes
(d) Ion-selective electrodes (ISE)	Potentiometric (voltage)	Ions in biological media, enzyme electrodes, immunoelectrodes
(e) Gas-sensing electrodes	Potentiometric (voltage)	Gases, enzymes, organelle, cell or tissue electrodes, enzyme immunoelectrodes
(f) Impedimetric	Impedance	Enzyme immunosensors
2. Piezoelectric crystals, acoustic devices	Mass change	Volatile gases, vapours and immunological analytes
3. Optoelectronic, fibre-optics and waveguide devices	Optical	pH, enzyme substrates, immunological analytes
4. Thermistors, diodes	Thermometry/calorimetric (heat)	Enzyme, organelle, whole cell or tissue sensors for substrates, gases, pollutants, antibiotics, vitamins, immunological analytes.

1. Conductimetric biosensors
2. Amperometric biosensors
3. Potentiometric biosensors
4. Piezoelectric biosensors
5. Optical biosensors

Conductimetric biosensors

The conductimetric principle of measurement is applicable to chemical systems because many chemical reactions produce ions and thus the conductivity of the solution is changed. Microconductimetric urea biosensors have been developed in which a small quantity of urea enzymes is immobilised over the sample pair of interdigitated serpentined network on the sensor (Fig. 2.47) chip by forming a cross-linked enzyme, i.e. albumin membrane with glutaraldhyde. When the test solution containing urea is placed over this membrane, decomposition of urea takes place which increases the overall conductivity of test solution.

Amperometric biosensors

Amperometric biosensors are also called enzyme electrodes. These sensors combine the specificity and selectivity of enzymes with the analytical power of electrochemistry. The method involves application of a constant potential between the sensing electrode and an auxiliary electrode in the test environment and measuring the resultant steady-state current. An amperometric chip is similar to a conductimetric chip, except that it contains two additional patterns; a counter electrode and a pattern in silver/silver chloride as reference electrode. The processing of these devices is therefore very similar to that mentioned earlier for conductimetric devices.

Potentiometric biosensors

Potentiometric measurements operate on the principle of accumulation of charge density at an electrode surface, resulting in development of a significant potential at that electrode. These sensors are mainly based on field effect transistors.

Piezoelectric biosensors

The functioning of piezoelectric biosensors is based on the principle of measurement of change in resonant frequency of piezoelectric crystal as a result of mass changes on its surface. These changes are caused by the interaction of test species with a biospecific agent, immobilised on the crystal surface. The frequency of vibration of crystal normally decreases as the analyte binds to the receptor, coating the surface. Such sensors normally operate by propagation of acoustoelectric waves along the surface of the crystal and are commonly referred as Surface Acoustic Wave (SAW) devices. A second generation SAW devices for detection of formation of antibody-antigen complexes in fluids are under development and testing stage.

Optical biosensors

The optical biosensors are becoming very popular, since the roles of superior fibre optics and optoelectronic transducers for measuring biological reactions have been realised. Enzyme reactions

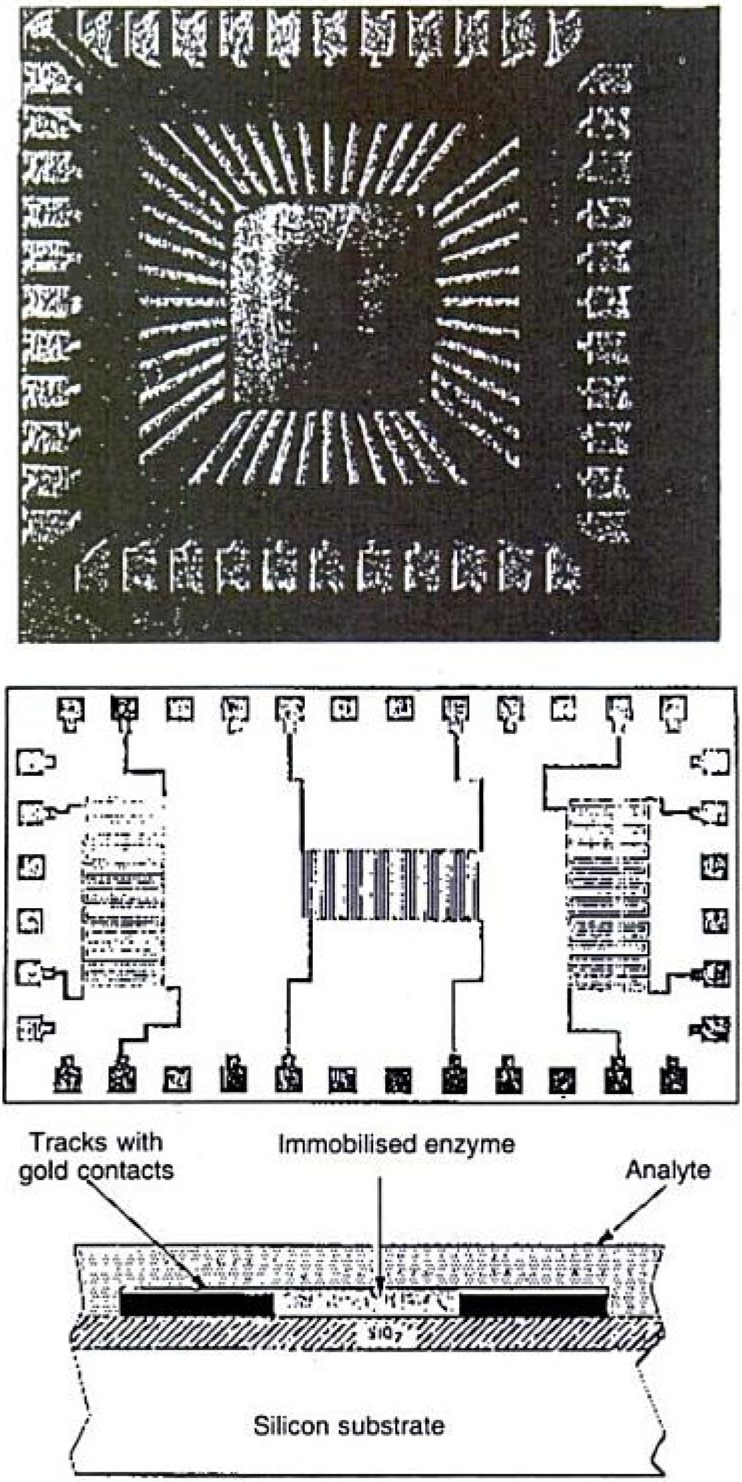


Fig. 2.47 (a) A microelectronic enzyme conductimetric device on a chip carrier, (b) Microcircuit surface, and (c) Cross-section of a pair of tracks with immobilised enzymes.

change the optical properties of certain substances. Light emission from biological element (bioluminiscence) or its response to illumination may be conveniently monitored via fibre or other optical wave-guide devices.

2.13 FUTURE TRENDS

The advancements in microelectronics technology are bringing forth new improvements in the silicon sensors. At present, the emphasis is placed on developing sensors which can be directly interfaced to microprocessors. These sensors (called digital sensors) incorporate signal conditioning unit as well as analog to digital converter unit on the same chip.

Researchers are also working on the development of intelligent sensors in various organisations. Intelligent sensor comprises a microprocessor (also on the same chip) and would be capable of carrying on limited processing. Integrated sensor with the microprocessor on the same chip has certain disadvantages too. Such a sensor may not be suitable for hazardous applications. In a hot, humid or caustic environment if microprocessor is put along with the sensor then the whole system may start behaving erroneously. However, in such applications, transmission of data to microprocessors at the remote locations may also have transmission problems. Large-scale improvements are expected in this technology in coming years and ultimately it may become possible to develop an integrated sensor plus microcontroller on the same chip, specialised for a particular application.

Another area of development being pursued is "Expert System Integrated Intelligent Sensors", i.e. Expert Sensor. Though it may take a number of years to achieve this goal, but with a provision of existing microprocessor, and AI technology, the goal looks feasible to achieve. Such an expert sensor would have on-chip signal conditioning circuit, powerful microprocessor and an expert system shell.

In the past several years, the development of optical sensors compatible with optical fibre transmission lines has become the goal of major research efforts. Much of these efforts have been directed towards fibre interferometric sensors, because they possess the following significant advantages:

1. Fibre interferometric sensors have potential for excellent sensitivity.
2. These sensors have unique automatic versatility.
3. These sensors have potential for detecting a variety of fields.
4. This capability makes multisensors fibre applications extremely attractive.

A typical configuration of a fibre interferometric sensor is illustrated in Fig. 2.48. Laser beam is split into reference and sensing fibres. The sensing fibre is suspended in water and exposed to the field to be detected, while the reference fibre is in an enclosed environment isolated from the field. The field to be detected induces an optical phase shift in the sensing fibre, relative to the reference fibre. A modulator is incorporated in the reference arm to provide frequency shift or modulation. Two beams are recombined on the beam splitter and detected by a photodetector. The signal is finally demodulated and with appropriate demodulation, fibre interferometric sensors can provide excellent sensitivity. The greatest advantage is the versatility as illustrated in Fig. 2.49. However, for the development of fibre interferometric sensors for various applications, more research on the demodulation techniques will have to be pursued. For an omni-

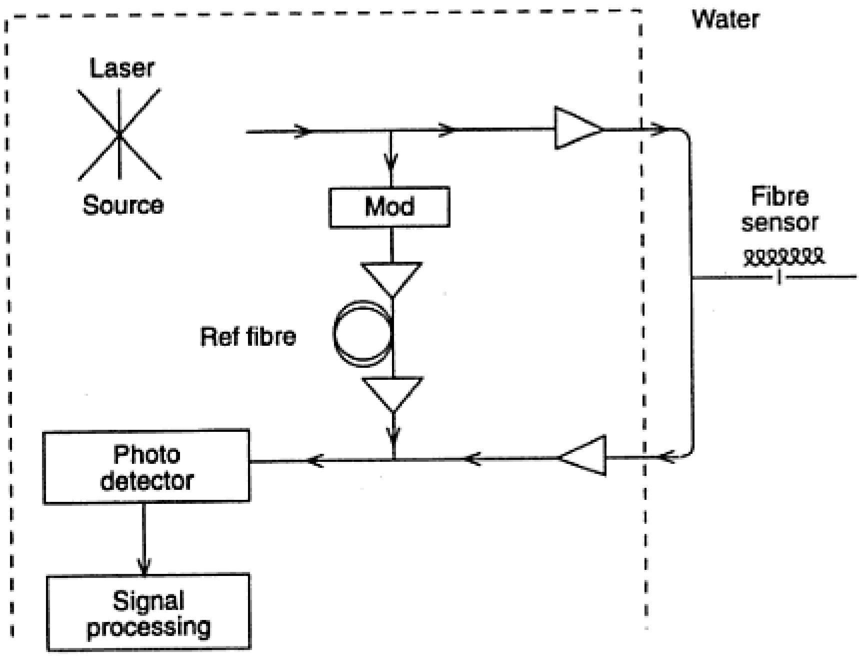


Fig. 2.48 Fibre interferometric sensor.

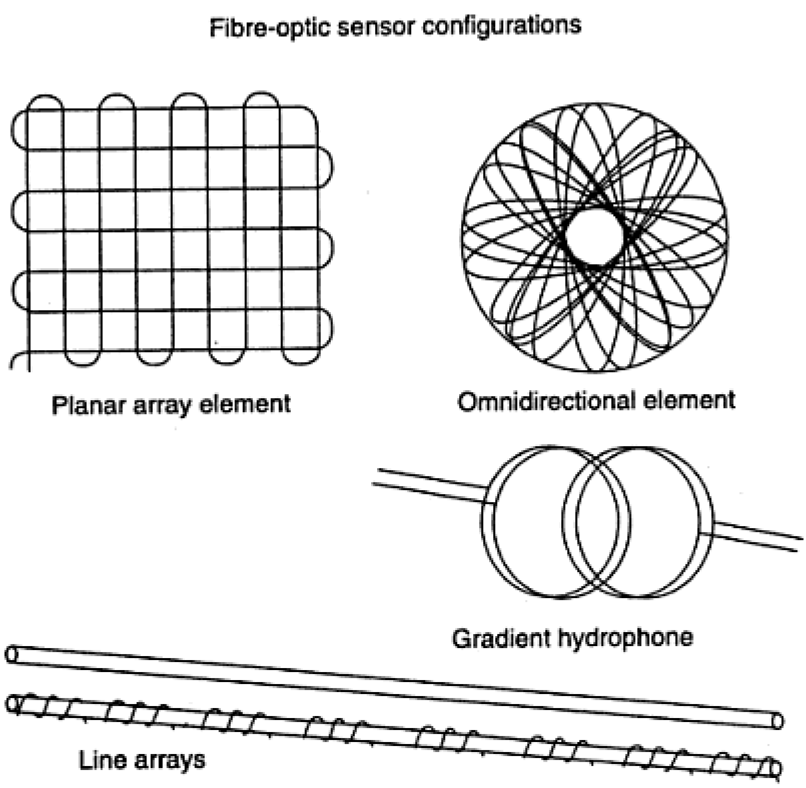


Fig. 2.49 Potential geometries for fibre sensors.

directional element, the sensor can be designed into any shape so long as it is small compared to wavelength.

It is quite clear that application of electro-optics and optical fibres for instrumentation is an important growth area in the immediate future. It is unlikely that sophisticated and expensive fibre optic systems operating well in scientific laboratory will be compatible to harsh environment of the process industries. What is required in fact is the availability of simple optical transducers with fibre-optic links. It is expected that research efforts in various parts of the globe will be directed towards this goal.

The biosensors are the product of fast emerging technology and it will take a few years before these are used widely in the industries. At present the limiting factors are robustness and shelf stability of biological sensing layers. The shelf instability problem, is overcome by storing the device under refrigeration which inhibits its use in industrial environment. A number of methods for immobilisation are under development to incorporate biological sensing element in membranes or gels, basically to increase the operational life of the devices. The main advantage of modified FET biosensors is its potential for producing a multisensor chip, incorporating an array of biologically sensitive devices with fully integrated signal processing and analysis circuitry. The FET device technology however suffers from problems of reliability, operating limitation and the fabrication.

It is expected that miniaturised conductimetric urea biosensors devices and associated instrumentation will find applications in blood analysis, urea determination and so on. The institutes which are actively involved in the development of biosensors worldwide are:

1. Institute of Chemical and Biochemical Sensor Research, Germany.
2. Technical University, Munich, Germany.
3. Cranefield Biotechnology Centre, Cranefield, UK.
4. Norwegian Water Technology Centre, Norway.
5. University of Lund, Sweden.
6. Institute for Technical Biochemistry, University of Stuttgart, Germany.
7. IGEC Marconi Material Technology, Casewell, UK.
8. University of Liverpool, UK.
9. *Centre de Recherche Public Hennri Tudor*, Luxembourg.

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3

Building Blocks of Automation System

3.1 INTRODUCTION

The development in the field of automation and in the field of intelligent machines (i.e. starting from computers, microprocessors to present day expert systems and neural networks) were almost simultaneous. It is a known fact that growth in computer and microprocessor technology was one single big cause for the growth in automation techniques like DDC, Distributed control, Adaptive control etc. In this chapter we shall be introducing the building blocks and systems that are used in automation system. We begin by introducing the computers and microprocessor advancements. The concepts of microprocessors, the facilities and advancements have been discussed briefly. The actual pins and signals, bus cycles, interfacing etc. have been avoided. The multiprocessor structures and local area network (LAN) structure have been described next. The multimicroprocessor system interfaced in tightly coupled common memory structure or in loosely coupled local area networks play very important role in distributed control or control involving large computation requiring high performance microprocessors. The other important building blocks of any control system, i.e. analog and digital I/O modules will be discussed in this chapter followed by Supervisory Control And Data Acquisition (SCADA) system and Remote Terminal Units.

3.2 PROCESSING SYSTEM

3.2.1 Computers and Microprocessors

The computers are predecessors to microprocessors. The basic concepts of computers were evolved before the dawn of microprocessor. The same concepts were extended in microprocessors to provide single chip CPU function in a microcomputer.

By the early 1970's, small integrated circuits (TTL Logic) were well established while MOS integrated circuits, such as calculator components had started to appear. The use of a minicomputer or control processor (as against the use of general purpose computers) was also well known. It was clear to some semiconductor engineers that if the calculator chip could become more general, it would have wider application. Also, the mini-computer users were confident that if it could be made more compact and cheaper its application areas will become further wide. These were the two mainstreams that led to the microprocessor development. Undoubtedly, what made the microprocessor possible was MOS technology and the remarkable properties of silicon, providing that, the microprocessor was inevitable.

Figure 3.1 shows the block diagram of computer showing different units and is known as Von Neumann Organisation of Computers. The computer organisation proposed by Von Neumann

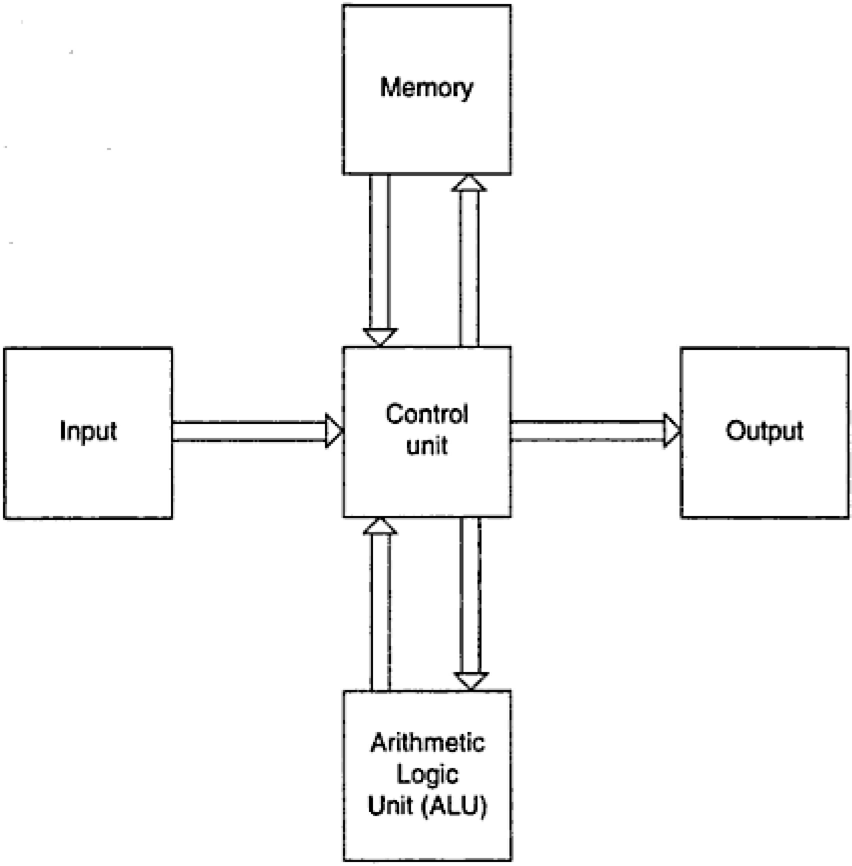

Fig. 3.1 Von Neumann organisation of computer.

envisages that binary number systems are used for both data as well as instructions. There is a direct correlation between the microprocessor organisation and the organisation proposed by Von Neumann for computers. Due to advancement in micro-miniaturisation, the arithmetic logic unit and control unit have been put on single chip and this chip is known as microprocessors. Figure 3.2 shows the computer organisation with microprocessor chip, memory input and output devices. The data bus will carry the data information and the control bus carries the control information like I/O Read, I/O Write, Memory read, Memory write etc. A generalised microprocessor structure has been shown in Fig. 3.3. A microprocessor will contain arithmetic logic unit (ALU), timing control unit, a number of scratch pad registers, stack pointer, program counter etc. Stack can be maintained in the memory along with programme and data area. The input/output units can be interfaced through I/O ports.

The idea here is not to describe the internal details of microprocessors, but to make readers aware of microprocessor structure and its advancements.

Every microprocessor will offer the following facilities:

(i) *Interrupts.* Interrupt is a facility provided by the microprocessor to the outside environment by which attention of microprocessor can be diverted to do some higher priority job.

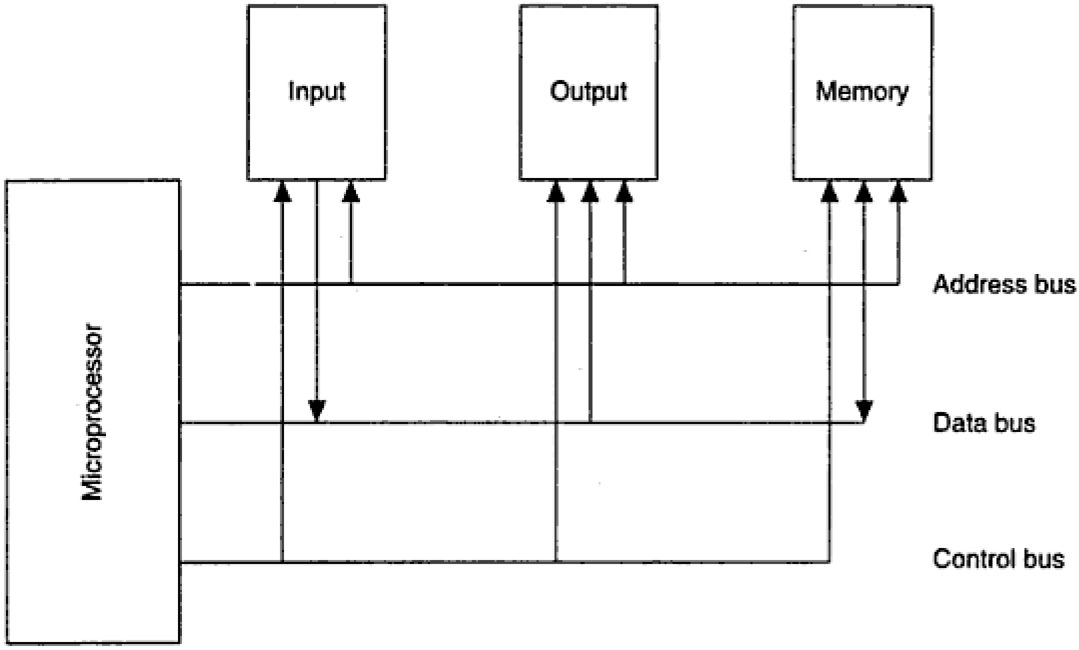

Fig. 3.2 Computer organisation with microprocessor chip.

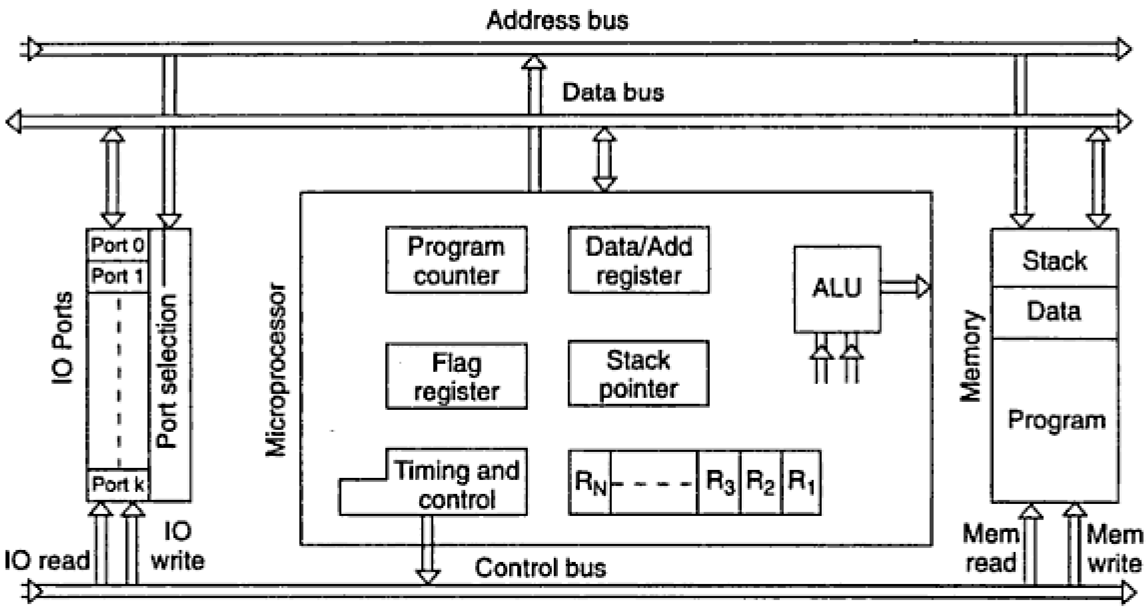

Fig. 3.3 A generalised microprocessor structure.

The interrupts are used for various purposes in different environments. Microprocessor can be interrupted to initiate data transfer, to execute control sequence, to control large power plants, or to check the status of a process at any particular instant. A number of interrupt request pins are provided by each microprocessor for this purpose.

(ii) *Direct memory access.* In order to facilitate the fast input/output devices for data transfer, microprocessor provides the facility by allowing them to transfer the data directly to or from memory. Microprocessors offer the facility through two pins—DMA Request and DMA Acknowledgement.

(iii) *Serial data transfer.* Some devices like teletype serial printers etc. are serial in nature. In addition to this, for long communication, serial communication is used to avoid skewing of bits. To minimise the number of interconnected wires, the data is transferred bit by bit on single line in serial communication. The microprocessors providing serial data transfer facility will have two pins for input and output of serial data and special software instructions to effect the data transfer.

3.2.2 Architectural Advancements of Microprocessors

A number of advancements that had taken place in the computer have migrated to microprocessor field with the continual advancement of microelectronics technology. The concept of multitasking, pipelining, and multiprocessing are already there in latest microprocessors. The pipelined microprocessors have a number of smaller independent units connected in series like a pipeline. Each unit is able to perform its tasks independently and the system as a whole is able to give much more throughout than the single microprocessor. The multitasking provides the environment in which the microprocessor can execute multiple tasks simultaneously by cycle stealing. The concept of virtual memory increases the memory capacity beyond the physical memory space possible through width of address bus. The Memory Management Unit (MMU) is now integrated on microprocessor chips. Thus microprocessors of 90s are equivalent to supercomputers of 80s and the process of growth is going to continue.

In the following sections, we shall discuss the evolution of microprocessors very briefly.

3.2.3 Evolution of Microprocessors

Typical of early microprocessors were Intel 4004, Rockwell PPSK, Burroughs Mini-d and Fairchild PPS-25, which were all calculator-based chips with emphasis on arithmetic operations. These had surprisingly good internal facilities (such as on-chip registers) but little emphasis was given to speed. The *P*-Channel MOS logic at that time was considerably slow in itself and the microprocessors were given a very small package (e.g. 16 pins) which required multiplexing of data streams.

8-bit microprocessors

The development in 8-bit microprocessor is due to the transition of microelectronics technology from LSI to VLSI technology and is based on *N*-channel metal oxide semiconductor work. With the high mobility of negative charged carriers (electrons) in *N*-channel MOS, higher logic speeds and greater packaging density than that in *P*-channel MOS was achieved.

Performance was improved by using a separate data and address bus with enough address bits for large amount of memory. On-chip registers addressed by the register addressing mode helped to speed up the programs. Instruction sets became more sophisticated with good arithmetic, data transfer and control facilities. The interrupt facility became standard.

With N-MOS, the microprocessors were able to drive the rest of the system without extra TTL chip, thus reducing the components count. Led by the INTEL 8080, every 8-bit microprocessor has its own peculiar characteristics.

Intel 8080, 8085

The 8080 microprocessor (Fig. 3.4) represented a dramatic improvement over 8-bit P-MOS 8008 microprocessor. The 8080 has a separate data and address bus but control signals are multiplexed on the data bus, requiring external latches to extract them. There are several on-chip registers but very few instructions can address the main memory directly; addressing being mostly register indirect. There are separate set of instructions for register, memory and input/output. Execution speed is quite high. There are useful interrupt and subroutine facilities. It requires external clock generator circuit and three supply voltages. The architecture reflected a switch to a parallel bus organisation though the system interface was still not clear. Since 8080 emerged earlier than other microprocessors, it became very popular and was taken as industry standard.

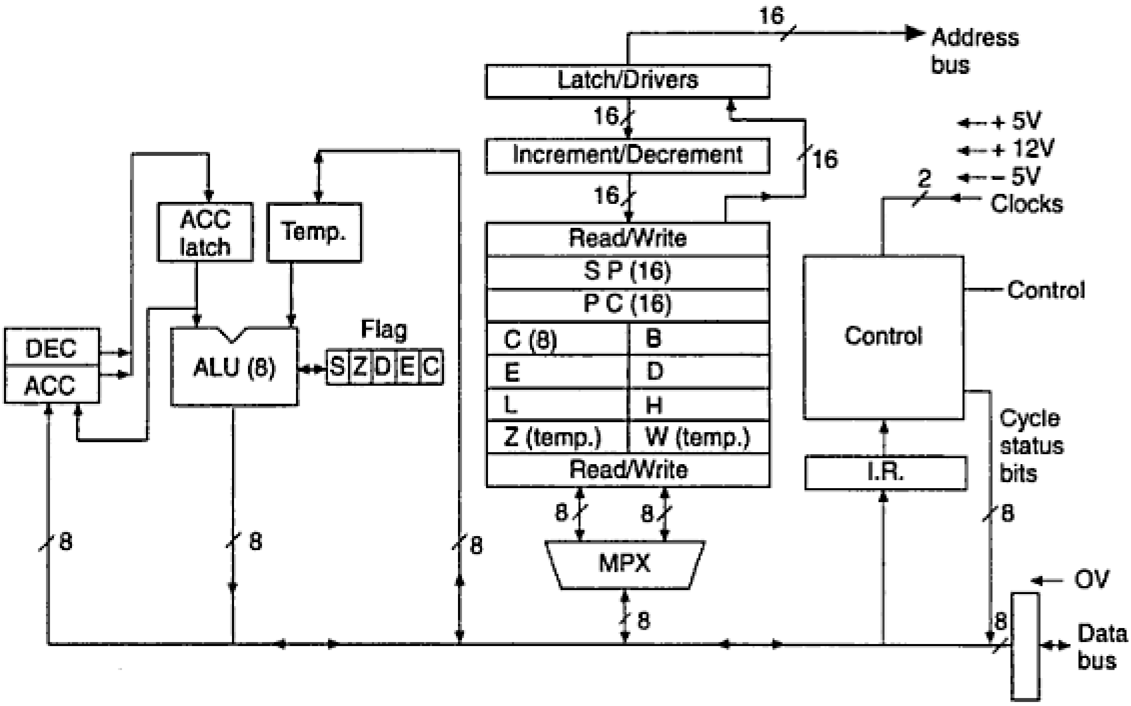

Fig. 3.4 Intel 8080 architecture.

The 8085 improved upon the 8080 for it needed only one +5V supply instead of three different voltages. The clock generator is integrated on-chip and the control lines need not be demultiplexed from the data bus. There are multiple interrupts provided on-chip. Yet the instruction set is almost unchanged and little extra speed is offered. On-chip serial input/output facility is present in addition. It has therefore been aimed to make a system easier and cheaper to build rather than to give higher processing performance.

Zilog 80

The Z 80 microprocessor was designed by the same team who created the 8080. It has twice as many CPU registers as the 8080 and many more instructions. In other ways its advantages over the 8080 are similar to the 8085's. The instruction set has more addressing modes which facilitates the development of shorter programs of greater speed. The designers have tried to make the instructions which appear most often in the program, to take up the least space and those which are executed most often the fastest.

Motorola 6800, 6802 and 6809

The approach adopted by Motorola for the development of their 8-bit microprocessor was quite different. The microprocessor has two accumulators but no general purpose data register on-chip. A parallel data bus concept was also adopted. All I/O devices are interfaced in memory mapped I/O. Good addressing modes (direct, page, indexed) and single level addressing (memory and I/O read/write use same instruction due to memory mapped I/O) made the program easy to learn. The fastest execution time (2 micro second) was similar to the 8080, but only a single low level clock and one +5 V supply voltage was required.

Later versions of 6800 (68A00, 68B00), are much faster than earlier versions because of changes in technology. The fastest instruction executes in 1 micro second (μs).

The 6802 has an on-chip RAM of 128 bytes but is slower. Otherwise, it is similar to 6800 with a clock oscillator on-chip.

Although an 8-bit machine, 6809 (Fig. 3.5) has many 16-bit characteristics. It has been made upward compatible with 6800. The CPU architecture, registers, and instruction set are extensions of 6800 format. The two accumulators of 6809 can be used together for 16-bit operations. There are four index registers (unlike only one in 6800) of which two are also used as stack pointers (U

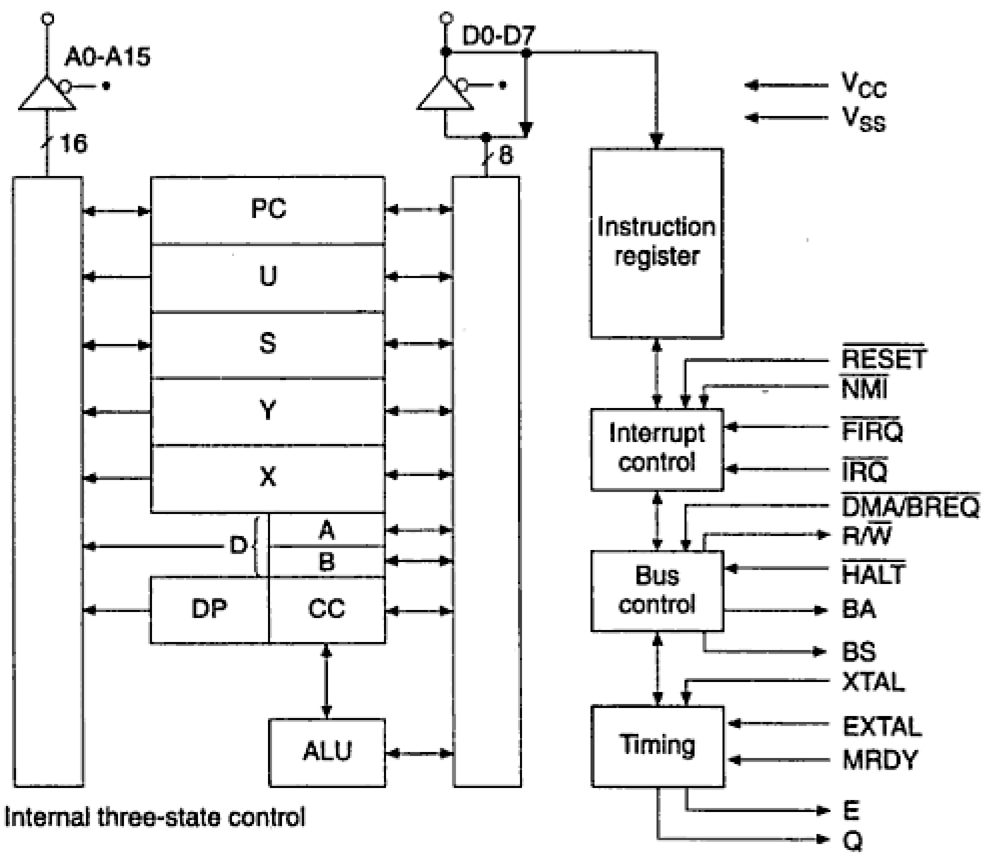

Fig. 3.5 MC6809 block diagram.

is the upper stack, S is for subroutine/interrupt stack). There is a page register (DP register) for short branch instructions. The addressing modes are numerous and useful and include variations on direct, indexed, indirect indexed etc. There is an 8-bit multiply instruction and 16-bit add, subtract, store and compare instructions. The 6809, therefore represents an attempt to offer an enhanced 8-bit microprocessor which is economical to use.

16-bit microprocessors

The advent of the 16-bit microprocessor was marked with certain new concepts like pipelining, virtual memory management, etc. Powerful addressing modes were evolved. Multiply and divide instructions were also introduced. The era of 16-bit microprocessor began in 1974 with the introduction of PACE chip by National Semiconductor, and CP 1600 by General Instruments. Several powerful microprocessors have been developed since then.

Intel 8086, 80186 and 80286

The 8086 (Fig. 3.6) was the first of the new breed of high performance 16-bit microprocessors. The HMOS technology allowed over 28,000 transistors to be used in the design and gave it a high speed. Memory components in HMOS are also very fast, down to less than 100 ns access time. It achieves its speed without needing fast memory components or even a separate data and address bus. The CPU consists of two parts, namely execution unit and bus interface unit. These parts act independently to achieve high speed. The bus interface unit maintains a queue of six instructions

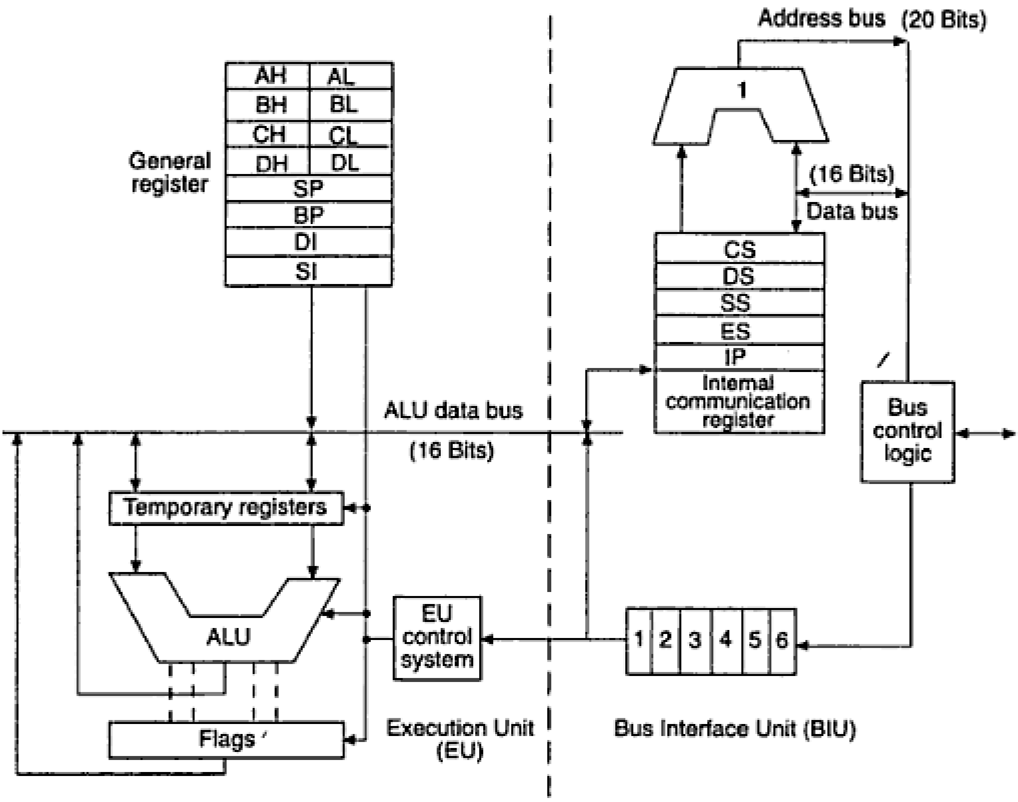

Fig. 3.6 8086 block diagram.

for execution unit. The memory is divided into four segments of 64 kilobytes each. The 20-bit address bus allows 1 million bytes of memory. The use of four segment registers (one for each segment) allows the program modules to be placed anywhere in the memory. 8086 also has two 16-bit pointers, two index registers and four 16-bit general purpose registers.

Powerful addressing modes and instruction set have been evolved. The microprocessor uses two address instruction and operation may take place between two registers, register and memory, register and immediate or memory and immediate. Memory addresses can be direct, indirect (via base or index register) or indexed (via base or index register). The processor can be operated in minimum or maximum mode by wiring a pin to +5V or ground.

The maximum mode allows multiprocessor environment. The 8086 instruction set is upward compatible to 8080 and 8085 with exception to RIM and SIM instructions. This compatibility is at the source level only.

The 8088 processor was introduced later than 8086. The internal structure of 8088 microprocessor is the same as its predecessor. The difference however lies in data bus which is 8-bit wide in case of 8088. The 8088 was introduced for systems which were originally designed around 8080 or 8085 and needed upward compatibility. The 8088 architecture is shown in Fig. 3.7.

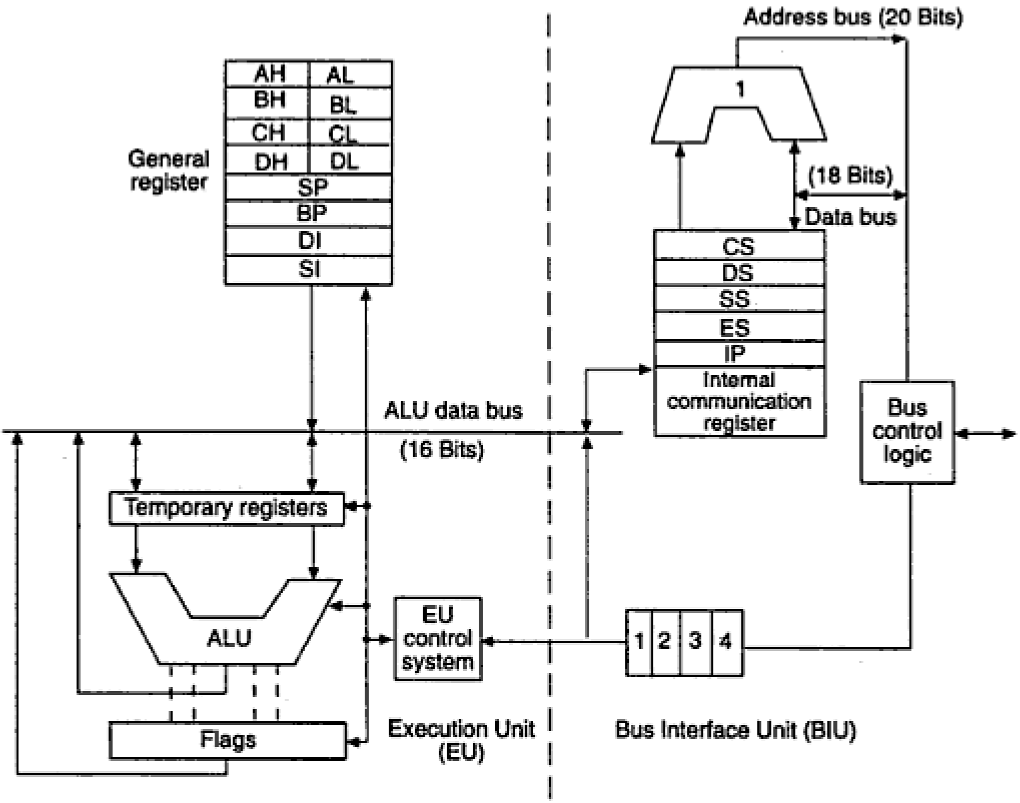

Fig. 3.7 8088 elementary block diagram.

The Intel 80186 (Fig. 3.8) introduced in 1982, offers twice the performance of standard 8086 and offers 12 additional instructions. Integrated on the chip are clock generator, DMA controller with two independent channels, three programmable 16-bit timers, 8086 CPU (8MHz version), etc. The multi-CPU configuration can be achieved through HOLD and HLDA.

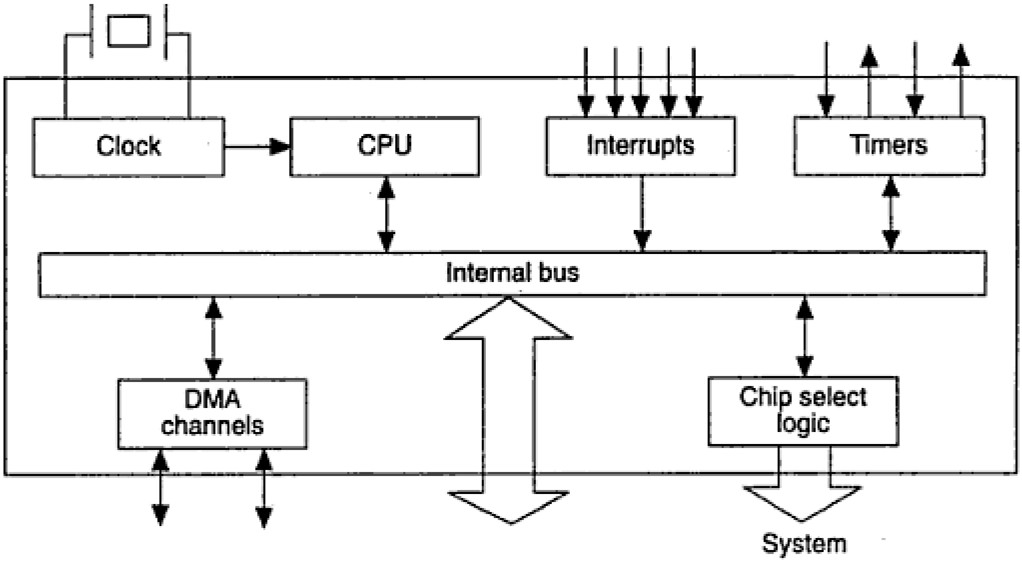

Fig. 3.8 Intel 80186 architecture.

The Intel 80286 also introduced in 1982, offers still higher performance, up to 6 times that of 8086. It has on-chip 10 MHz processor (8086), memory management unit with four level memory protection and support for virtual memory and operating system. It supports 16 megabytes physical and 1 gigabytes virtual memory. The 80286 uses a superset of 80186 instruction set with sixteen additional instructions. This processor is specially designed for multiuser and multitasking systems.

Zilog 8000

By using VLSI techniques, Zilog have managed to pack an extremely powerful 16-bit microprocessor on a single NMOS silicon chip. Two basic versions of Z8000 are being produced. Z8001 a segmented addressing system allows access to 23-bit address bus and permits up to 8 million 16-bit words or 16 megabytes of memory to be used. Z8002 is non-segmented version with 64 kilobytes memory. It is possible to use Z8000 in multiprocessor environment. Z8000 does not have a dedicated register for use as the accumulator. Instead it uses a bank of sixteen general purpose 16-bit registers any of which may be used as accumulator. Memory in the Z8000 system may be divided into areas for system and user and also into separate data and program areas which are all defined by status control lines from the processor. The main addressing modes provided by Z8000 are register, indirect register, direct, immediate, indexed, relative, base address and base indexed. There are 110 basic instruction types which may be executed on various modes to give over 400 different types of operations.

Motorola 68000

The MC68000 (Fig. 3.9) is quite different from other 16-bit processors in many respects. Though it is a 16-bit microprocessor, it has largely 32-bit wide data organisation and a flexible array which gives it a very high processing throughput. Hardware multiplication and division logic are included on the chip. This further increases the processing speed in complex calculations. Twenty three address bits provides 16 megabytes of direct addressable memory space. No dedicated

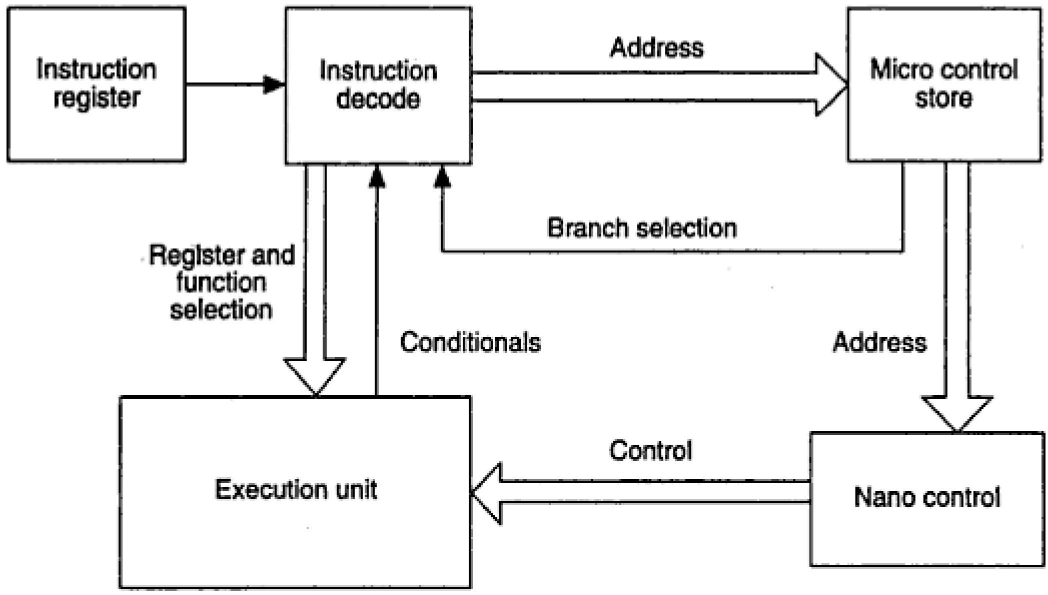

Fig. 3.9 Motorola 68000 architecture.

accumulator has been provided, instead it uses a bank of eight 32-bit general purpose registers D0–D7, of which any register can be used as accumulator. The system is able to handle 32-bit operations with ease.

Fourteen different basic addressing modes are provided on the MC68000. There are 56 basic instructions type in MC68000 instruction set. Combined with the addressing modes, they form a powerful instruction repertoire.

32-bit microprocessors

The era of 32-bit microprocessor began in 1981 with the introduction of iAPX 432. In 1980 IBM implemented IBM 370 CPU on a single chip but since it is not offered commercially, this is generally overlooked. Other 32-bit processor are Belmac-32A microprocessor from Bell Labs, the 32-bit CPU chip from Hewlett Packard, INTEL iAPX series, Motorola 68020 and 68030 etc.

Intel iAPX 386

80386 a 32-bit member (Fig. 3.10) of iAPX 86 family. It is software compatible to 8086, 8088, 80186 and 80286. New concepts like caching, pipelining are provided along with high performance bus, and high speed execution unit. The 80386 provides two to three times the performance of 80286. It has pipelined architecture with parallel fetching, decoding, execution and address translation inside the CPU. It provides full 32-bit architecture and internal implementation including 32-bit register file, instruction queue, address translation unit, address bus and data bus. It has hardware supported multitasking and virtual memory support. The physical memory up to 4 gigabytes can be addressed whereas the virtual memory up to 64 terabytes can be addressed per task. It has hardware enforced protection up to four levels to provide protection of sensitive code data within a task. The general purpose registers of 80386 support 32-bit data and addressing. They also provide for 8 and 16-bit compact addressing.

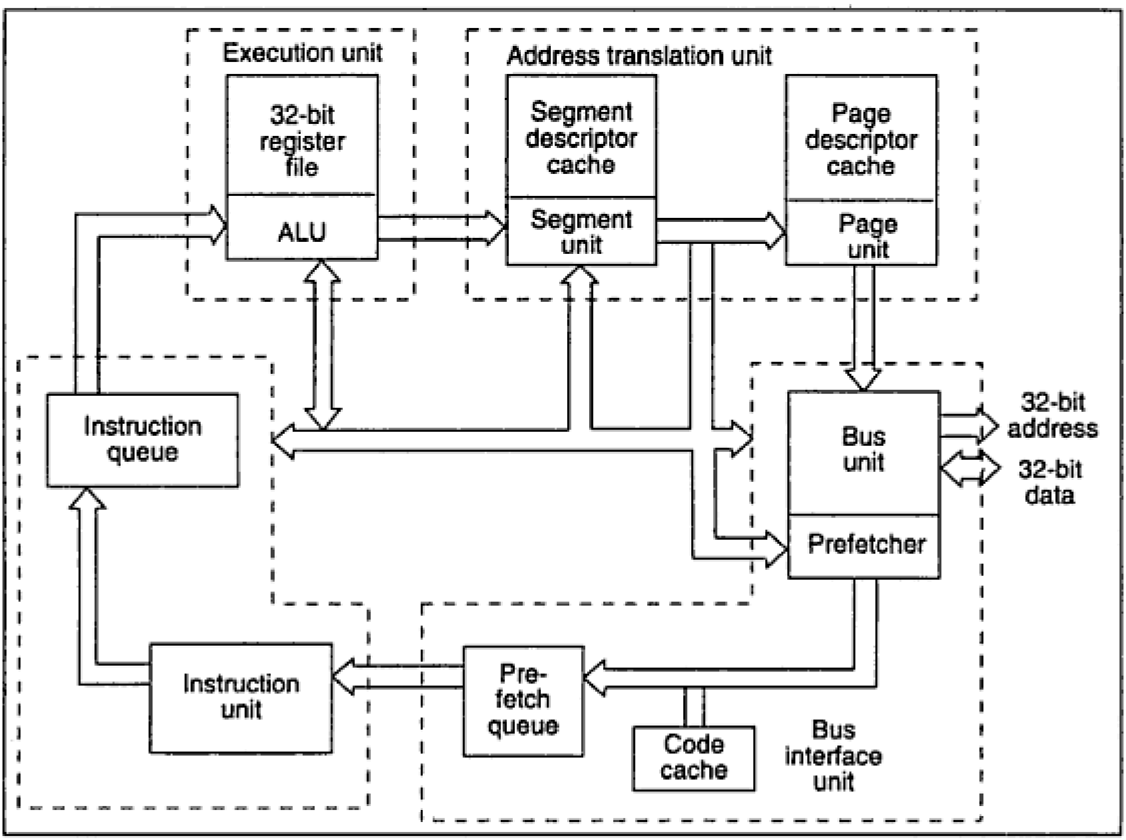

Fig. 3.10 iAPX 386 pipeline.

Motorola 68020, 68030

Motorola 68020 (Fig. 3.11) is a 32-bit virtual memory processor. It has fast on-chip instruction cache to improve execution speed and bus bandwidth. It is object code compatible to 68000. The

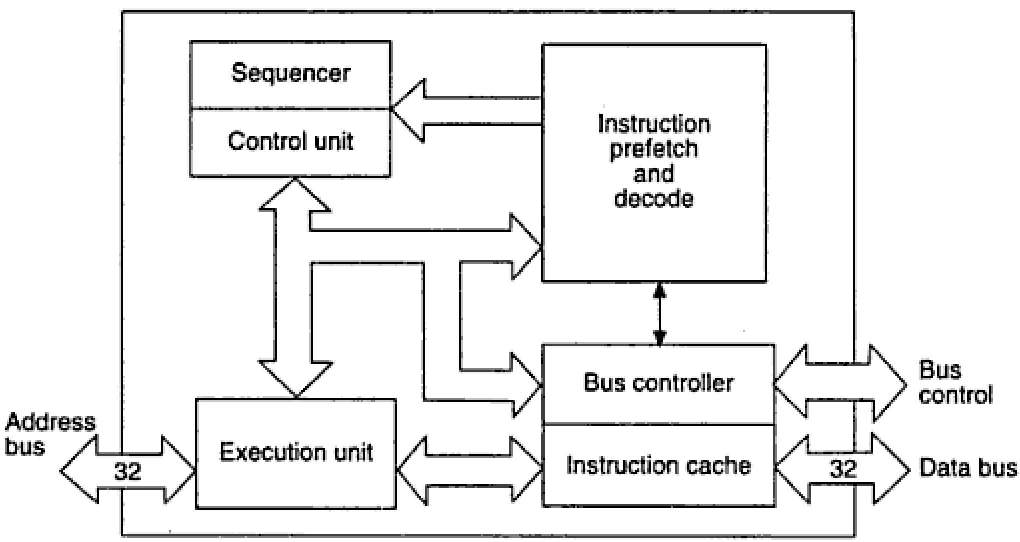

Fig. 3.11 68020 block diagram.

pipelined architecture has high degree of internal parallelism, which allows multiple instructions to be executed concurrently. The processor has sixteen 32-bit data and address registers, and supports 18 addressing modes and 7 data types. Four gigabytes memory can be directly interfaced. The clock frequency can be 12.5, 16.67, 20 or 25 MHz.

Motorola 68030 (Fig. 3.12) is second generation 32-bit enhanced microprocessor based on 68020 core. It is object code compatible with 68020 and 68000. The paged memory management unit translates addresses in parallel with instruction execution. The processor contains 256 bytes instruction cache and 256 bytes data cache. The clock frequency can be 16.67 or 20 MHz.

Intel iAPX486

iAPX486 is an advancement over iAPX386 microprocessor series of Intel. It contains pipelined structure having arithmetic logic unit, cache unit, bus interface, instruction decode, prefetch check and floating point unit. It is upward compatible with 8086 and is widely used (Fig. 3.13).

Intel's pentium processor

The pentium processor, the newest and the most powerful member of Intel's X86 microprocessor family, incorporates features and improvements made possible by advances in semiconductor technology. A super-scaler architecture (Fig. 3.14), improved floating point unit, separate on-chip code and write back data cache, a 64-bit external data bus and other features like branch prediction, multiprocessing support etc. provide platform for high performance computing.

Intel i860

It is 64-bit microprocessor that delivers the kind of power and capability associated with super computers. It integrates super computer features like 64-bit architecture, parallelism and vector processing and takes full advantage of advanced design techniques like reduced instructions set computing, pipelining, score boarding, by-passing, delayed branching, caching and hard-wired 3-D graphic instructions. It incorporates a risk integer unit, a floating point unit, a 3-D graphic processor, data and instruction cache, memory management and a bus control unit (Fig. 3.15).

Bit-slice processor

AM2901 bit slice processor is available in a slice of 4 bits. Depending on the word size required, more than one slices can be connected to form a higher bit processor, i.e. 8-bit processor can be obtained by connecting two slices, 12-bit processor by connecting three slices, and so on. The IC chip is based on bipolar technology. Thus these processors are faster than processors based on N-MOS technology. User level microprogramming is offered in bit slice processor. These are most suited for special applications.

3.2.4 Microcomputers and Microcontrollers

Microcomputers are microprocessors with on-chip memory. Some microcomputer chips contain timer/counter, interrupt handling, also along with processor and memory Timer/counter and interrupts are useful for control application and these microcomputers are called *microcontrollers*. In some cases analog to digital converter and digital to analog converter have also been integrated on the chip. There is a variety of microcomputers/microcontrollers from different manufacturers like 8048, 8051 and 8096 series of Intel, Z8 from Zilog, M6801 and 68HC11 from Motorola,

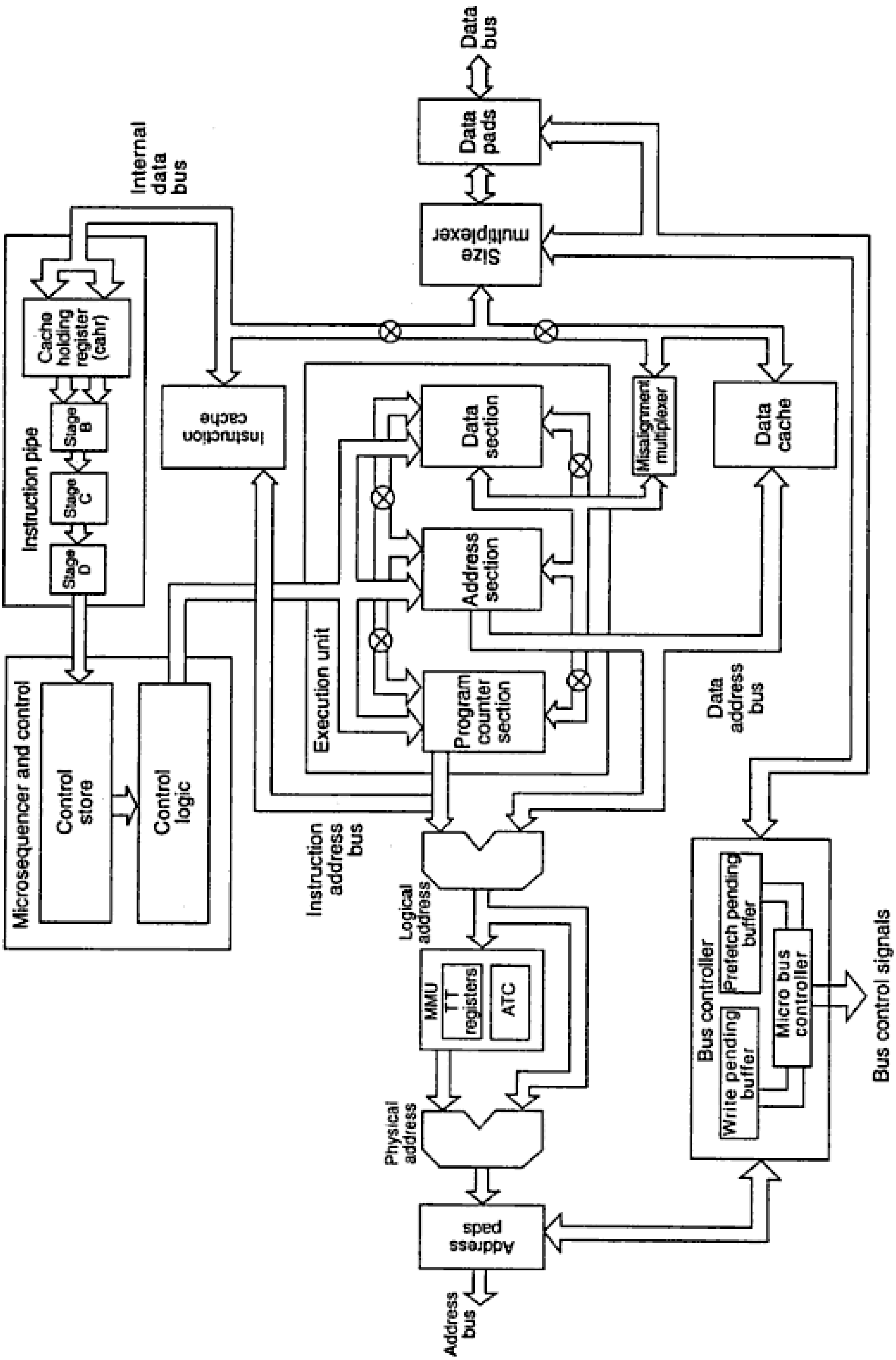

Fig. 3.12 68030 block diagram.

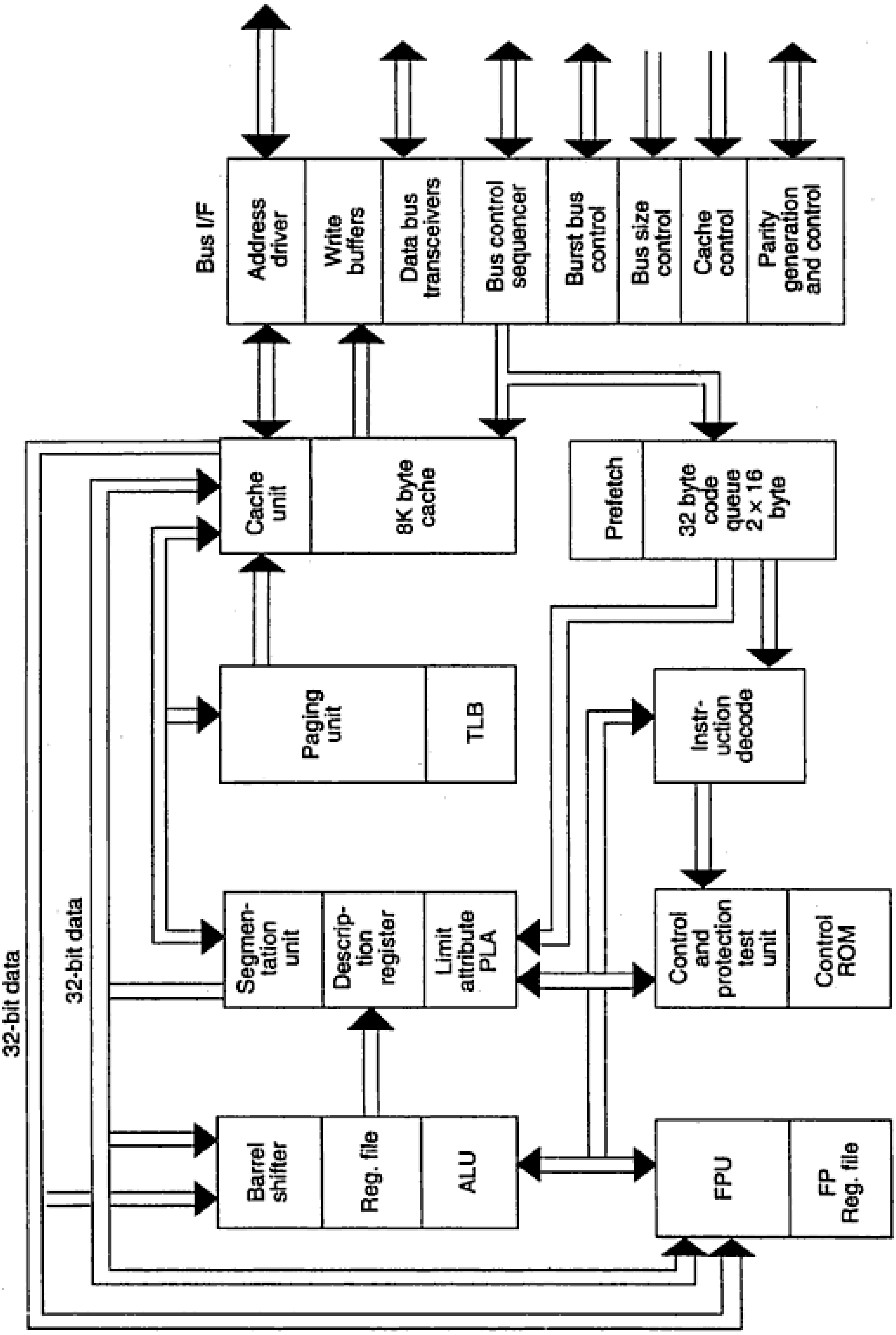

Fig. 3.13 Intel 80486 block diagram.

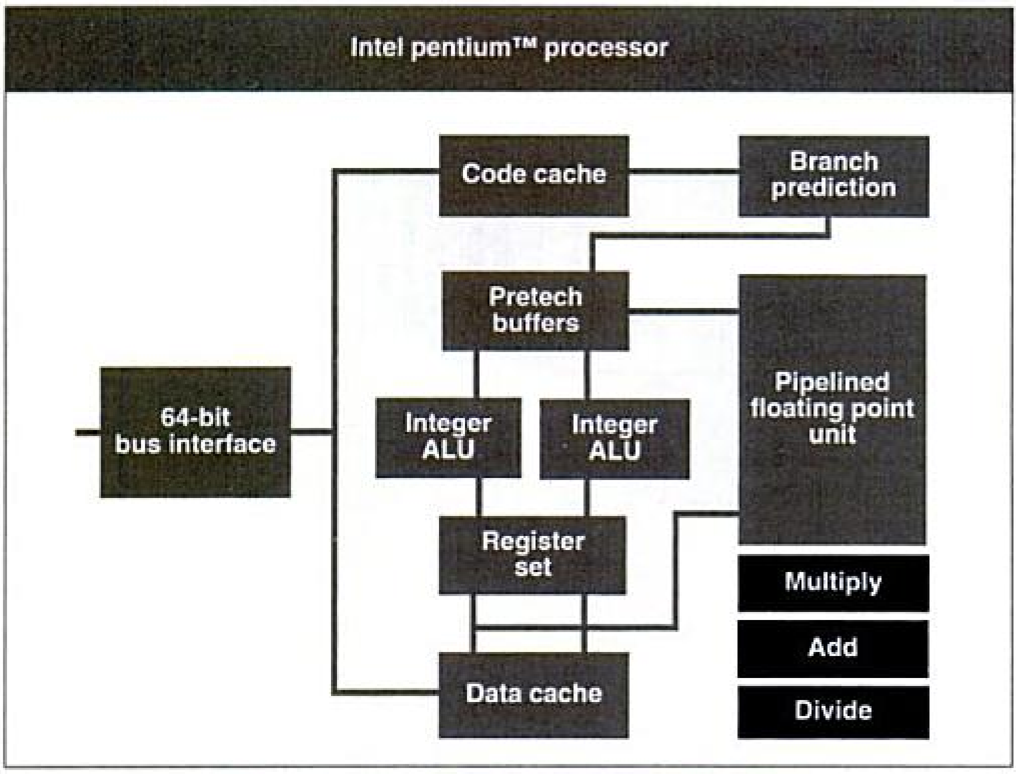

Fig. 3.14 Intel's pentium processor architecture.

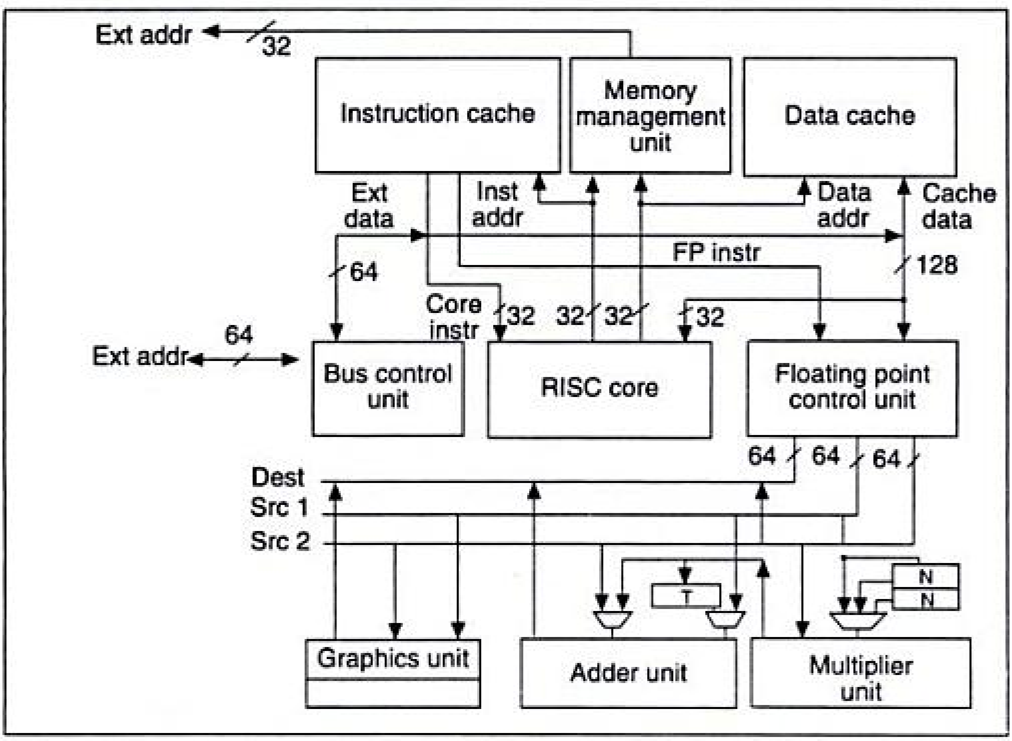

Fig. 3.15 Intel i860 block diagram.

1650 series from General Instruments, IM6100 from Internal Inc. etc. In general, these chips come in three versions namely "on-chip ROM version", "on-chip EPROM version" and "ROM-less version". The later two versions are used for development purposes. After the development is complete, the large number of 'on-chip ROM' version chips can be obtained by getting the program fused at source, at low cost.

Intel 8051 series

Intel 8051 microcontroller (Fig. 3.16) is an 8-bit microcontroller with on-chip 8-bit CPU, 4 kilobytes of RAM. 21 special function registers, 32 I/O lines and two 16-bit timer/counter. It offers 64 kilobytes address space for external data and 64 kilobytes of address space for external program memory, a five source interrupt structure with two priority levels, a full duplex serial port and bit address capability for boolean processing. Intel 8031 is a ROM-less 8051 and 8751 is an 8051 with EPROM instead of ROM. Software instruction include powerful multiplication, division, bit set and bit test operations.

Intel 8096 series

16-bit microcontrollers of (MCS-96 series) (Fig. 3.17) of Intel are extensions of 8051. CPU supports bit, byte and word operations including 32-bit double word operation. Four high speed trigger inputs are provided to record the time at which external events occur, six high speed pulse generator outputs are provided to trigger external output at preset times. The high speed output unit can simultaneously perform timer functions. Up to four such software timers can be in operation at one time.

An onchip A/D converter converts up to 4 (8095, 8395) or 8 (8097, 8397) analog input channels to 10-bit digital value. Also provided on chip are a serial port, a watch dog timer and a pulse width modulated output signal. 8 kilobytes of on-chip RAM is available in case of Intel 8396, 8394, 8397 and 8395 whereas 8096, 8094 and 8095 are ROM-less version. As stated earlier A/D conversion is available only with 8095, 8395, 8097 and 8397.

Motorola 68HC11

The Motorola 68HC11 is an 8-bit microcontroller (Fig. 3.18). It has internal 16-bit address bus. It has at least 512 bytes of EEPROM and is available in more expensive versions with either 2K or 8K of EEPROM. The motorola 68HC11 has five parallel ports. Any line not serving the specialised alternate as shown in figure, can serve a more general functions. The other facilities include 8 channel, 8-bit ADC, serial port, programmable timer, UART port etc.

3.2.5 The Transputer

The principle behind the design of the transputer is to provide the system designer with a building block component which can be used in large numbers to construct very high performance systems. The transputers have been specifically developed for concurrent processing. The on-chip local memory assists in eliminating processor to memory bottlenecks and each transputer supports a number of asynchronous high speed serial links to other transputer units. The efficient utilisation of processor's time slices is carried out by a micro coded scheduler.

The transputer to transputer links provide a combined data communications capacity of 5 megabytes/sec. and operate concurrently with internal process. This is a radical difference from

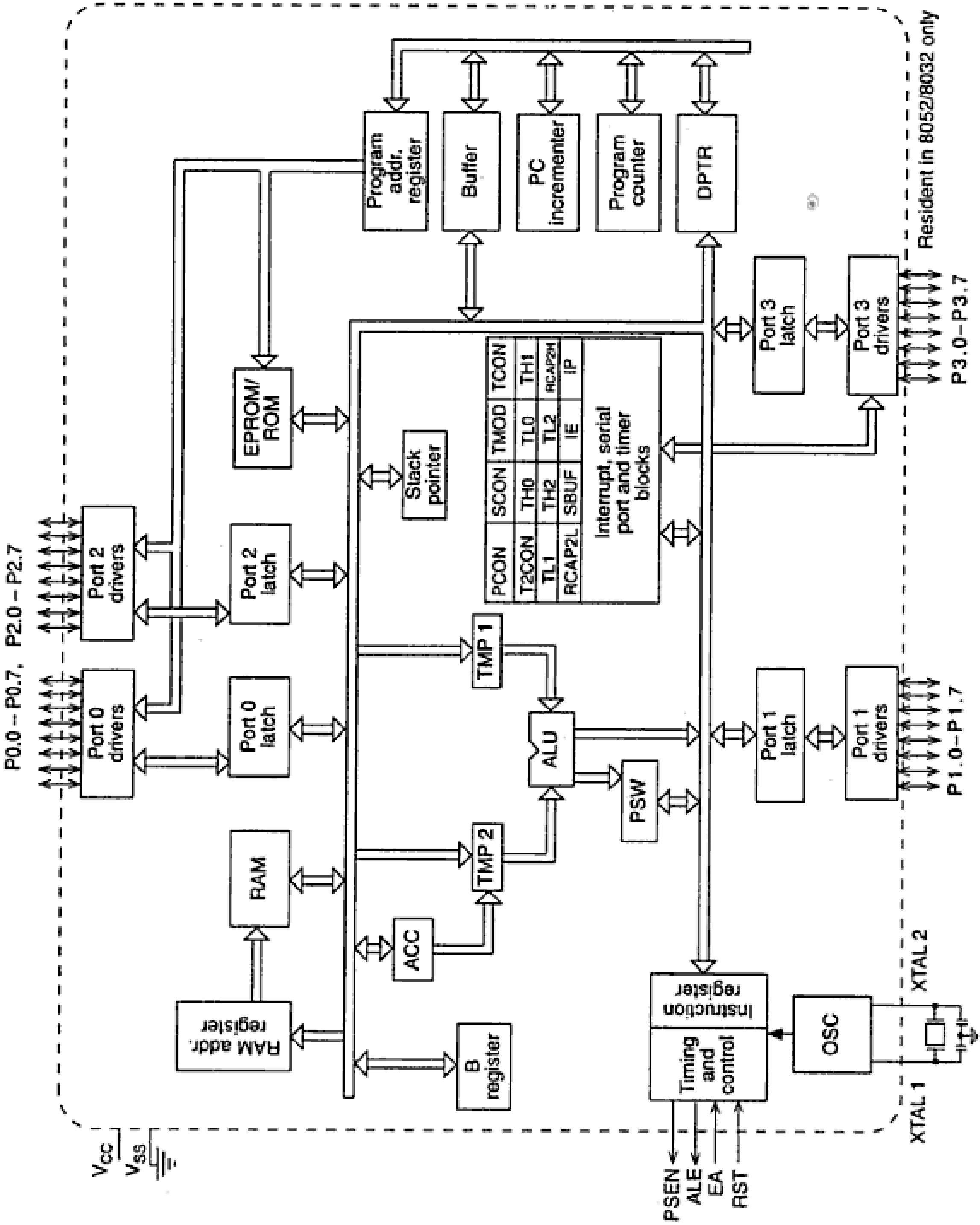

Fig. 3.16 Intel MCS-51 architecture.

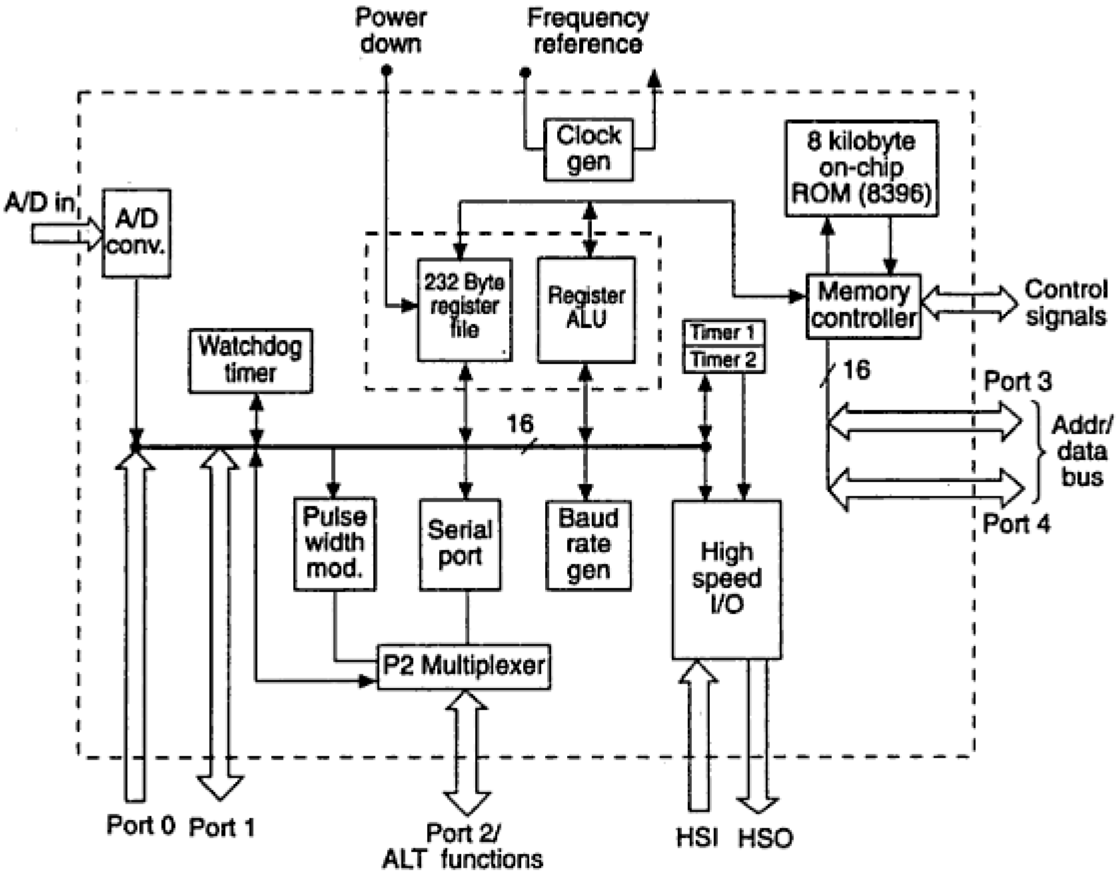

Fig. 3.17 MCS-96 architecture.

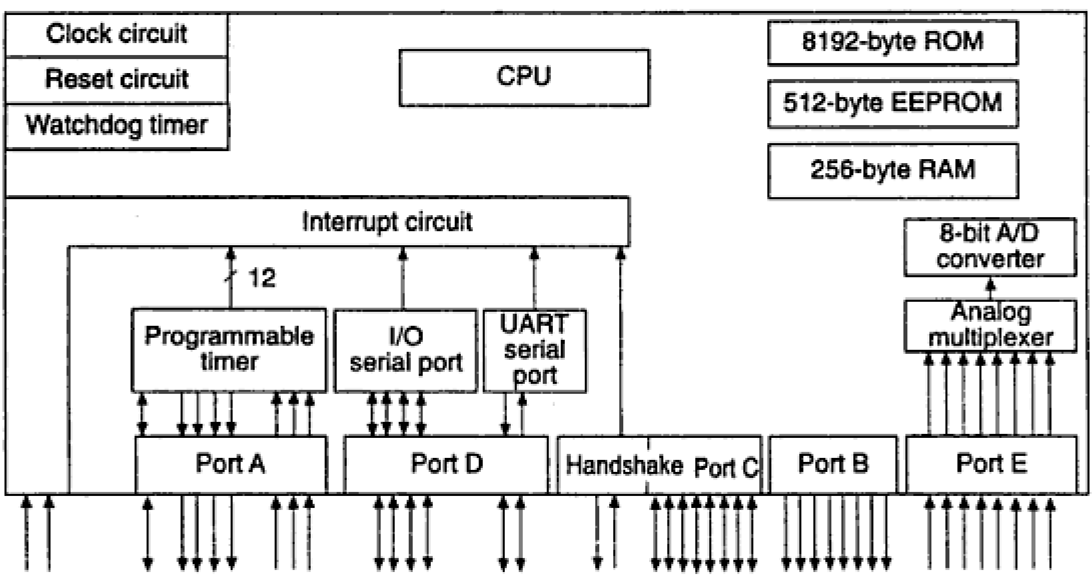

Fig. 3.18 Motorola 68HC11 microcontroller architecture.

the shared bus concept employed in the majority of multiprocessor architectures. It allows parallel connection without overhead because of the complex communication between conventional parallel processors. The advantages over multiprocessor buses are as follows:

1. No contention for communication.
2. No capacitive load penalty as transputers are added.
3. The bandwidth does not become saturated as system increases in size.

The system supports high level concurrent programming language. Occam specifically designed to run efficiently on transputer systems. The Occam allows access to machine features and removes the need for a low level assembly language.

Figure 3.19 shows the architecture of IMS "T-800 T-30" transputer. The main features of this chip are (a) Integral hardware 64-bit floating point unit, (b) 2.25 sustained megaflops/sec., (c) Full 32-bit transputer architecture, (d) 4 kilobytes on-chip RAM for 120 megabytes/sec. data rate, (e) 32-bit configurable memory interface, (f) External memory band width of 40 megabytes/sec., (g) High Performance Graphics Support, (h) Single 5 MHz clock input-DRAM refresh control, (i) Four 10/20 megabits/sec. INMOS serial links, (j) External event interrupt—Internal Timers, (k) Support for run-time error diagnostics. Boot from ROM or link etc.

3.3 MULTIMICROPROCESSOR SYSTEMS

The architecture proposed by Von Neumann was Single Instruction Single Data (SISD) stream. A number of computers have been designed around this structure. The architecture of various microprocessors, as discussed in previous section is also based around Von Neumann architecture. The single instruction and single data stream computers are easy to conceptualise and design since the computer is executing only one instruction at a time. The data flow is from/to only from one input/output unit at an instant. Multitasking concept was used for increasing the speed of program execution. This allows a number of programs resident in the computer's memory at one time. The computer switches from current task to other task as and when an I/O instruction is encountered. Since I/O units are comparatively slower than CPU, the computer on encountering the I/O instruction, initiates its execution and then starts executing another program. On completion of I/O, the computer gets signal to switch back to the original program. This optimises the CPU time. However, the branch and return addresses as well as the status of various programs are to be maintained by CPU. A number of new concepts have been introduced both in computers and microprocessors with the aim of increasing the speed, by incorporating parallelism in memory and processing. These concepts are:

1. Parallelism in memory
   — Interleaving
   — Cache memory
   — Multiple memory access
2. Parallelism in processing
   — Pipelining
   — Pipeline vector processing
   — Parallel processing

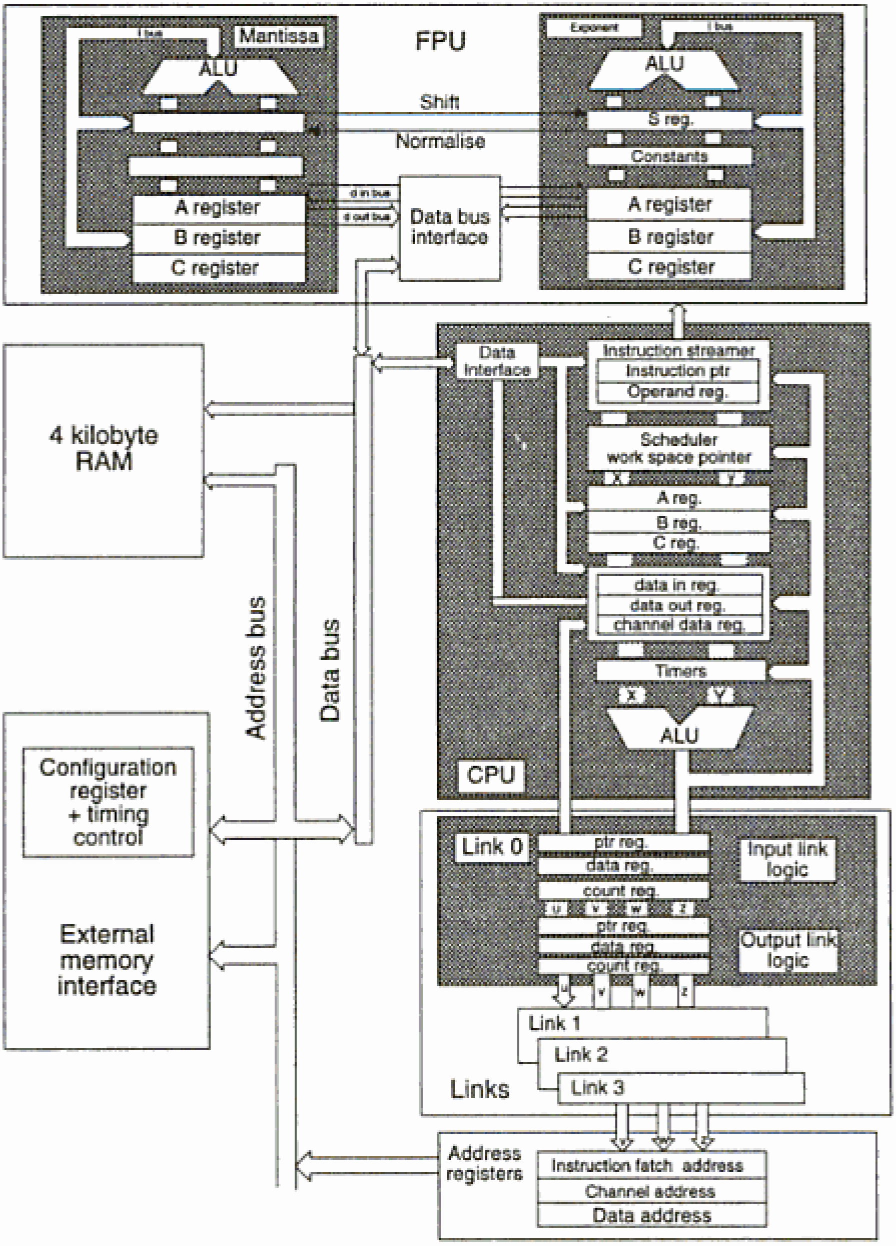

Fig. 3.19 IMS T-800-30 transputer architecture.

Most of the above concepts have found their way to microprocessors. The pipelining, cache memory, vector processing etc. are widely used in todays high-performance microprocessors.

It was however clear that parallelism is necessary for increased speed which is measured by Millions Instructions Per Seconds (MIPS) executed by the CPU. It was thought that instead of SISD architecture, data and instruction stream can be increased. The classification of computer architecture with respect to data stream and instruction stream is shown in Fig. 3.20. Other equally important reasons for introducing parallelism was reliability through redundancy in control systems and geographically or functionally distributed control systems.

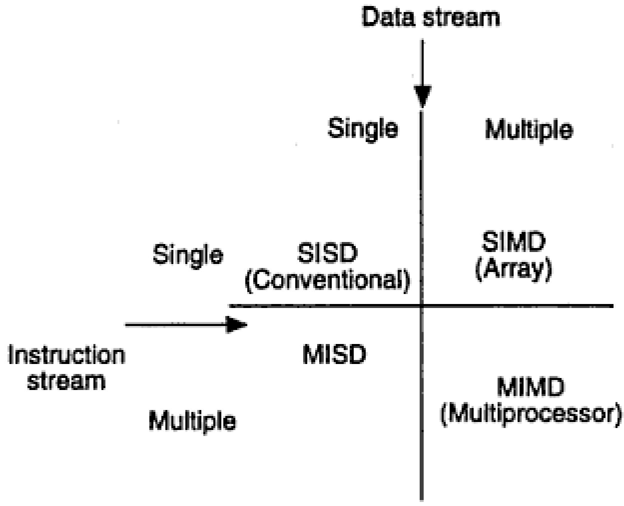

Fig. 3.20 Classification of computer architecture.

The parallelism may be required in the systems due to various reasons. Some of the reasons are discussed below:

Performance

The performance of a system increases due to dedicated hardware for a particular task. In multi-microprocessor system, the independent parallel tasks for any application where a system is to be used, should be identified. These tasks should be allocated to individual processors, in order to increase the performance i.e. the speed of the systems, manifold. The overall performance upgradation will be decided by a number of factors like execution time of individual tasks, total number of parallel tasks, and also the type of processors used etc.

Reliability

In many of the processes, it is imperative that the systems should function satisfactorily even in case of hardware or software failures. This results in duplication of the system elements and external resources. As an example, in the avionics, the expected mean frequency of failure per 10 hours flight is 10^{-9}. The conventional microprocessor frequency of failure is 10^{-2} to 10^{-5}. If a microprocessor based system is used for avionics application then it has to be suitably replicated to increase the reliability. In case of process industries also, similar but less stringent reliability criteria will exist and will amount to multiprocessor system for fail safe operations.

Distributed applications

There are number of applications in which the plant is distributed. For example, in case of offshore oil distribution, where the various distribution nodes are independent and are situated quite far from each other. In such applications, each node is managed by a separate microprocessor. These nodes work parallely and report to a single supervisory computer. Similar applications are found in number of other industries, like steel, refineries, etc.

General purpose computers

There is often a conflict regarding high MIP ratings and low cost among the designers of general purpose computers. The test is to provide cost effective general purpose computer with increased performance. Since the entire computer field is flooded with micros, the general approach is to put more number of microprocessors together to achieve higher MIP ratings. However, it cannot be said that if the MIP ratings of single microprocessor was 1 MIP then by putting 4 of these together one would have the ratings of 4 MIP computer. This proportional relation does not exist due to overheads by operating systems and memory management.

Super computer design

There are certain applications which are beyond the scope of general purpose computers and are governed by very high MIP ratings. Some of these applications are weather forecasting, aerodynamic modelling, astrophysics etc. The purpose of using multimicroprocessor systems is same as that in case of general purpose computer, i.e. higher MIP ratings. However, the cost ceases to be a criteria in such systems.

3.3.1 Microprocessor Interconnections

There are a number of ways microprocessors may be interconnected to form a single multi-microprocessor system. These are: (a) Shared Bus; (b) Multiport memory; (c) Bus window; and (d) Cross bar switches.

All these techniques use common memory space between different microprocessor systems. The memory space also serves as interface between different microprocessors. The interconnecting bus is parallel. It may follow S-100, IEEE 488 or IEEE 796 bus standard. A number of systems have been designed using Intel Multibus also. The temporary interconnection follows Master-Slave configuration. The parallel bus has lines for address, data, control, interrupt and bus exchange. The bus exchange lines allow several masters to share the bus so that they can communicate with the slaves in an exclusive manner. Such a bus system can operate with a 10 MHz clock transmitting 16-bit addresses and 8/16-bit data in parallel.

Shared bus

The Shared Bus multiprocessor architecture is basically a Master-Slave Configuration in which Master Device requests for bus and communicates with slave device. In this configuration *Processor* is always designated as *Master* and *Memory* always as slave. This provides temporary link between two devices that need to communicate. At any given instant only one master-slave relationship can exist over a bus. The system may have many processors which will compete for becoming master by getting control on the bus. The concept is same as in Intel Multibus System. The concept of shared bus is shown in Fig. 3.21. The Shared Bus must resolve the request received from many competing masters. Bus arbitration therefore, plays a very important role in the shared bus. Following three signals are involved in bus arbitration:

— Bus **Busy Line**

— Bus **Request**

— Bus **Acknowledge**

The Bus arbitration is essential to grant control of bus to one of the competing masters who

Computer-Based Industrial Control

Krishna Kant

Combining design concepts, theoretical concepts, application examples, besides a number of case studies, this is a comprehensive textbook dealing with computer based control area which is the basis of present day automation. The book considers that designing system for real-time process control can be achieved if the designer is able to understand the subject conceptually.

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