PART 1

MECHANICAL DESIGN OF ELECTRONIC SYSTEMS

CHAPTER 1 INTRODUCTION

1.1 OVERVIEW AND OBJECTIVES

This book has been prepared to serve as a text for students and entry level persons beginning to design electronic systems. The coverage begins at the interface between electrical engineering and mechanical engineering and pertains to the mechanical, materials, manufacturing and assembly issues which arise in developing a new electronic or computer system. The treatment is quite broad starting with integrated circuits (the chip) and proceeding through the many levels of packaging involved in developing a complete electronic system. The material is often highly descriptive, particularly when compared to the mathematical treatments presented in more mature subjects such as mechanics or the design of mechanical components. However, the descriptive material is important in introducing the essential vocabulary, which is full of acronyms, and to present the wide array of electronic components that mechanical and electrical engineers must deal with in the design process.

This book is divided into four parts to organize the material and to facilitate understanding by the reader. Part 1 covers background material including semiconductor physics, analog circuit theory, digital circuit theory and transmission line theory. The objective of this background information is to give the engineers involved in mechanical design of electronic systems, often called packaging, the basic understanding as to why and how electronic circuits operate. Experience has shown that this information greatly enhances communication between the mechanical and electrical engineering functions in a development project, and enhances the opportunity for successful concurrent product development instead of sequential development.

Part 2 involves packaging beginning at the first level where the chip is housed in its carrier, and then extending through the higher levels to the design of the cabinets and instrument panels. The word packaging is poorly understood by the engineering community where it is often confused with the design of a container to prevent damage during shipment of a product. Packaging of electronic systems refers to the placement and connection of many electronic and electro-mechanical components (sometimes thousands) in an enclosure which protects the system from the environment and provides easy access for routine maintenance. An example which describes some of the important features of packaging is illustrated in Fig. 1.1. The packaging process starts with a chip which has been diced from a wafer of silicon that was fabricated using photolithographic semiconductor fabrication processes. The chip contains electronic devices (e.g. transistors, resistors, etc.) that are interconnected in a planned manner to form integrated circuits (IC's) that perform a desired electrical function. After testing, the chip is housed in a chip carrier and small wires or solder balls are used to electrically connect the chip to the carrier. The chip carrier or component is often referred to as the first level of packaging, while the electrical connections to the chip carrier are called the first level of interconnects. Next, several chip carriers are placed on a circuit board or substrate (second level of packaging), and connected together with wiring traces (second level of interconnects) which have been formed by photoetching the circuit board. Edge connectors on the circuit boards are then inserted into contacts on a back panel (third level of packaging) which carries the higher level connections that permit communication from one circuit board to the next. Cables are shown which connect the power supply to the back panel and which bring the input and output (I/O) signals to and from the unit. Finally, the entire array of circuit boards, back panels, power supplies and cables are housed in a cabinet (fourth level of packaging). The packaging aspect of the design of an electronic system is extremely important as often more than one-half of the cost of a system is involved in packaging.

Part 2 also describes materials and manufacturing methods used to fabricate printed circuit boards including those made from glass reinforced plastics and multilayered ceramics. Mechanical, electrical and thermal properties of metals, glasses, polymers and ceramics used in electronic systems are discussed. The coverage includes all aspects of the manufacturing process including material selection, tooling, drilling and cleaning. Photolithography used to pattern the footprint of each layer is described in detail. Finally, solder materials and processes used to connect the terminals of the electronic components to the bonding pads on the printed circuit boards are also covered.

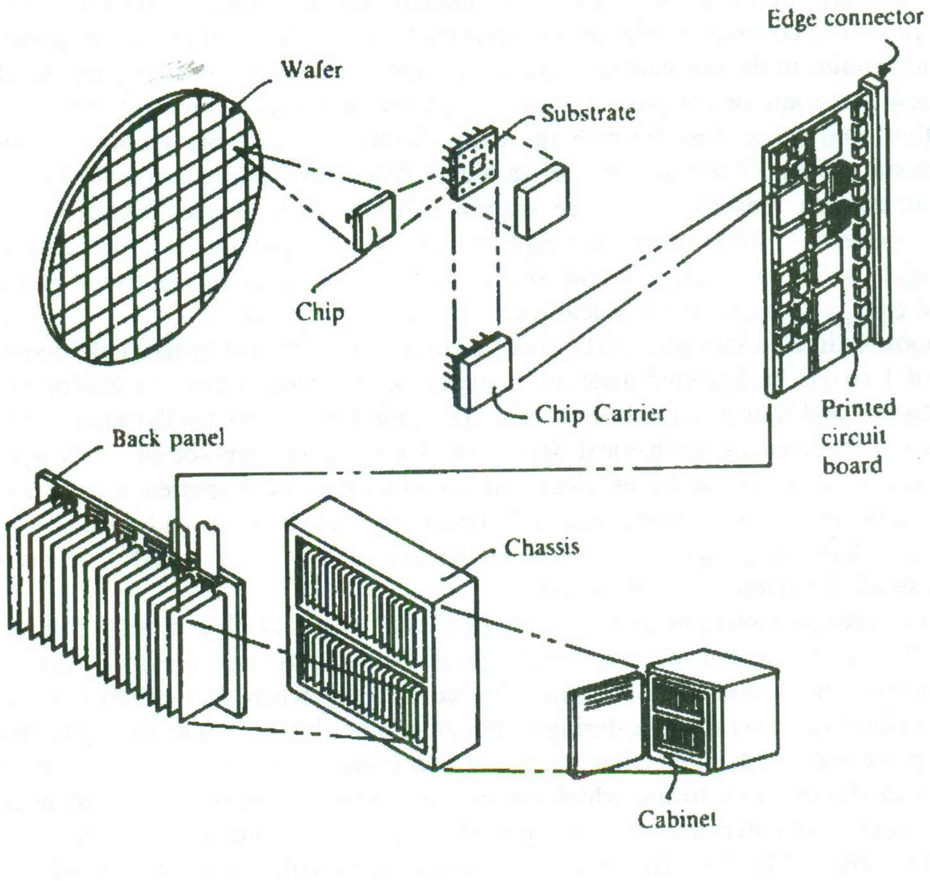

Fig. 1.1 An illustration of several levels of packaging involved in an electronic system.

Part 3 deals with analytical, experimental, and numerical methods used to insure the reliability of electronic systems exposed to harsh environments. In addition to carefully packing potentially thousands of electronic components into a stylish and functional cabinet, packaging involves the protection of these components from the environment. Thermal management is one of the most important of the environmental considerations, as the operating temperatures of the chips markedly affect the reliability of the circuits and the availability of a system. Thermo-mechanical loadings and stresses in the assembly will result due to temperature changes caused by powering the system on and off, or by changes in the local ambient environment. For electronic systems destined for use in the field by either the military or industry, shock, vibration and humidity represent harsh environments which must be accommodated in the design of the hardware. Finally, noise is an important consideration particularly in air cooled equipment where one or more fans are used to move significant volumes of air.

Part 4 deals with designing an electronic system for reliability. This treatment has two main components—a discussion of failure mechanisms, and analysis emphasizing the use of reliability theory and statistics. Techniques used to enhance reliability or system availability are also discussed.

In this presentation, simple examples will be selected which emphasize basic theoretical approaches and which illustrate sound design concepts. In actual practice, the real problems will be much more complex but the applicable theory and the design concepts are the same. In many organizations performing the design of electronic systems, special codes or software exist for handling some of the complexity associated with very large electronic systems. We will recognize some of these approaches in this book, but we will not describe them in any detail because they change rapidly with time.

1.2 FUNCTIONS INVOLVED IN MECHANICAL DESIGN OF ELECTRONIC SYSTEMS

Electronic packaging serves four major functions in the performance of electronic systems, which include:

1. Interconnection of electrical signals at several levels of packaging.
2. Mechanical and environmental protection of the components, circuits, and devices
3. Distribution of power to the electronic circuits and devices.
4. Dissipation of the heat generated by these devices.

These four functions are the basic drivers advancing the state of the art in packaging technology.

It is important to understand the differences in the advancement of semiconductor and packaging technologies. Semiconductor technology has been generally following Moore's law, which predicts the rate of scaling of the minimum feature size on semiconductor devices. With reduced feature sizes, more devices and more functions can be fabricated on a specified chip area for each succeeding generation of semiconductor devices. The ability of the semiconductor industry to follow Moore's law is discussed later in this chapter (see Fig. 1.16). Although some packaging elements have been scaled to match the reduced dimensions of the semiconductor input and output (I/O) pads, the dimensions of most of the other packaging elements cannot be scaled down at the same rate.

There are several reasons for the inability of the packaging industry to markedly reduce the features size in the different levels of packaging. First, at the external inputs/outputs, the connections must be sufficiently large to be able to be handled by human scale peripheral devices. Second, excessive reduction of the cross-sectional area of the circuit lines on the second and third level circuit boards results in increasing line resistance that degrades the signal as it propagates and increases the heat that must be dissipated. Third, increased I/O at the chip level has generated the need for more expensive area array interconnections, such as flip-chip solder balls, to replace less expensive wire bonds to perimeter pads; thus, causing a general increase in the cost of packaging a system. Fourth, increased power densities from high-performance chips have placed severe demands on the power distribution system to deliver high currents and then to dissipate high power levels from individual chips. The first level chip carriers must house chips that are becoming larger in area with each new generation. Increase density of transistors on each chip results in increased power levels that require more aggressive cooling technologies. Finally, the mechanical and environmental protection mechanisms do not scale.

As the microelectronic industry continues to develop chips with more dense circuits that require increasing amounts of power, efficiently packaging the array of new products will be a significant challenge. Packaging costs, which often exceed the cost of the associated microelectronic chips, will become even more important in the design of all but the highest performing systems.

1.3 MECHANICAL DEVELOPMENT OF ELECTRONIC SYSTEMS

A mechanical development department is usually responsible for packaging electronic systems in most industrial firms that produce an extensive line of electronic products. Because large electronic systems are usually quite complex involving several different engineering disciplines, multi-department organizations are usually established to handle the logical flow of paper, CAD files and other information generated in a typical development project. An example of one organization is shown in Fig. 1.2. The development process is initiated (in large firms at least) by corporate planners who identify customer needs and predict market trends and technological advances. With this information as a basis, they prepare the specifications for a new product indicating performance requirements, market estimates on volume, costs, price, and other higher level design objectives. Development budgets and schedules are also part of the output from the corporate planners.

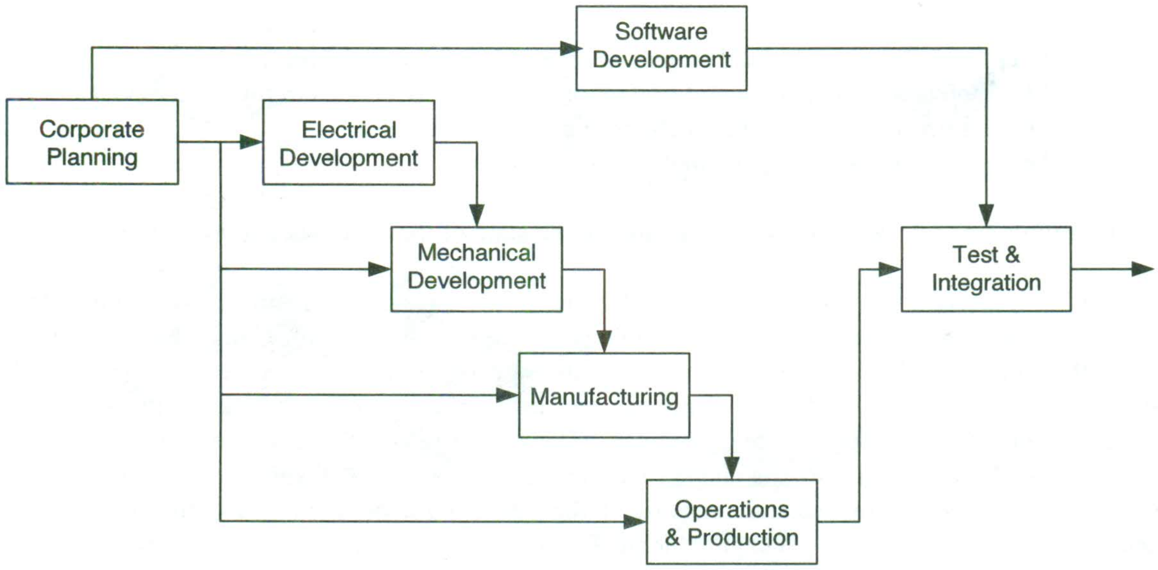

Fig. 1.2 Typical organization used in developing an electronic product showing information flow and discipline interfaces.

The project moves from the planners to the electrical or computer engineering department where the system architecture is established and then the detailed analog and digital circuits are designed. The output from electrical or computer engineering department is passed on to mechanical engineering department in the form of circuit diagrams, logic diagrams, component lists, wiring lists and ground rules for component layout and shielding requirements for the cables. The output from the electrical or computer engineering department also goes to the computer science department where the code necessary to operate the system is written.

The mechanical development department packages the system by sizing and designing circuit boards, placing components on each board and connecting the appropriate pins on each component. Back panels and power distribution busses are designed in conjunction with gates, chassis drawers and cabinets. Connectors and cables are designed to ensure connectivity as well as access for routine maintenance. A cooling system is designed to carry away the heat that is dissipated by the many different electronic devices employed in constructing high performance systems. Operating panels that are appreciated by the operator and the customer are developed to be attractive, functional and ergonomic. The system is designed to accommodate the operating and storage environments as described by the controlling specifications. The output from the mechanical development department is in the form of drawings, CAD files, and reports describing analyses predicting response of the system to the environment and its reliability. This output is transmitted to the manufacturing and operations departments.

Manufacturing engineers design and build the tooling necessary to manufacture the components, sub-assemblies, circuit boards, cables, etc. The circuit boards, back panels, sub-assemblies, cabinets, etc., are fabricated and then assembled into the final product. This manufacturing process is quite challenging particularly during the assembly and test of the first few units. Operation engineers insure that all materials and components are available on time for the assembly of the system. They also oversee the production process and control both the input and output inventory. Design errors are discovered during the early production period and close cooperation among mechanical development, manufacturing and operations is essential to develop design modifications that correct the errors without incurring high costs. Design for enhanced manufacturing is a critical objective in developing a product known for its quality as well as for its performance.

The prototype moves from operations to unit test where the performance of the circuits and the software are evaluated. This phase, often called debugging, requires close cooperation between the electrical engineers and the software personnel. Mechanical engineers are involved in recording the electrical changes (so called soft or white wires) so that the changes in connections can be made on revised circuit board layouts and cable drawings. Unit evaluation may involve shock, vibration, temperature cycling or other accelerated life type testing for product qualification and reliability evaluation. If failure occurs with the hardware, the mechanical engineer is responsible for the diagnostics and for the design modifications required to improve the package to adequately protect the system from the environment imposed during product qualification.

The design of smaller electronic systems is usually accomplished by a team of engineers who are all located in close proximity. The engineering disciplines described in the previous paragraphs are all represented on this focused development team. Because the system under consideration is relatively small, only a few engineers from each discipline are required to complete the development in a timely manner. The advantage of the team structure over the functional organization, described previously, is that the design process is less formal and rapid communication is enhanced. The disadvantage is that the depth of knowledge and expertise of the team members, in one or more disciplines, may not be equivalent to that found in the more heavily populated departments in a functional organization.

1.4 MECHANICAL DESIGN ASPECTS OF PACKAGING

There are ten main issues involved in the design of an electronic system as indicated below:

1. Connections
2. Thermal management
3. Cost
4. Performance
5. Manufacturing
6. Maintenance
7. Thermo-mechanical deformations
8. Shock and vibration
9. Reliability
10. Ergonomics

The priority order of the issues is dependent on the product under consideration. In many high end products, performance is more important than cost. In other applications, reliability (or system availability) is more important than performance. In high volume products, cost and performance are usually balanced. In products used on military platforms, the ability to survive in intense shock and vibration environments is critical. In most products, each of these issues markedly affects the design, and close attention is necessary in every area to insure that the design specifications are met or exceeded.

1.4.1 Connections

In advanced electronic systems, it is easy to define at least six levels of connections. We start with the bonding pads on the chip and connect these pads to the I/O leads on the chip carrier. This normally accomplished using small wires or solder balls. For example, the photograph in Fig. 1.3 shows small diameter gold wires that have been thermosonically bonded to the I/O pads on the chip and its associated chip carrier. Second, the leads from the chip carrier are connected to the printed circuit board (PCB). These connections normally involve the design of solder joints and the trace routing on the PCB; both are very important tasks. Third, connections are made between the different PCB's which exist in the system. There are several different approaches to connecting PCB's depending primarily on the complexity and size of the system. For small simple systems containing only a few PCB's, the connections are made with edge card connectors, which are cabled together. However, for large systems, which may contain many PCB's, the connections are made with edge card connectors, which are inserted into a back panel or motherboard. Many layers of circuit traces that are photo etched on each layer of the back panel serve as a very compact form of cabling. Fourth, the back panels, which usually are housed in a cage, drawer or gate, must be connected together to permit one sub-system to communicate with another. The number of connections, at this fourth level, is reduced to primarily sub-system I/O and power; hence, the signal connections are usually made with cables and the power connections are made with heavy wires or bus bars capable of handling high currents. The fifth level of connection involves wiring the back panels to the I/O connectors within the cabinet or enclosure. Cable harnesses for signal I/O and bus bars for power distribution are commonly employed. The sixth and final level of connection occurs in very large systems where cabinets and or work stations are connected together. The methods employed for cabinet to cabinet connections depend largely on the distance between cabinets and the speed required in transmitting signals. For short distances, these connections are usually made with twisted pairs of wire or coaxial cable. For longer distances, only coaxial or fiber optic cables are sufficient. For very long distances a dedicated set of cables becomes very expensive and transmission is accomplished with common carriers such as phone lines, microwave transmission or fiber optic transmission lines.

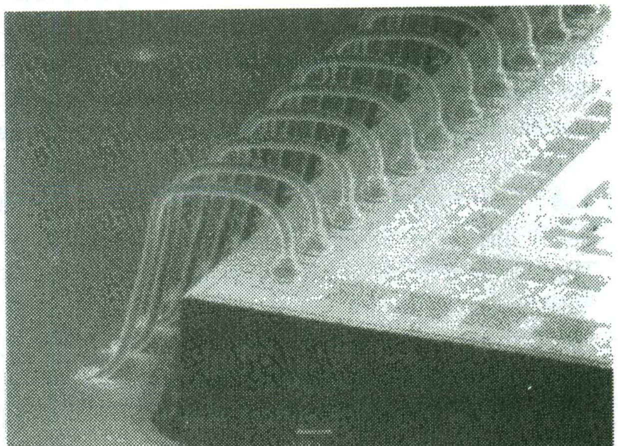

Fig. 1.3 Enlargement of a corner of a chip showing small diameter gold wires connecting the chip I/O to the lead wires on the chip carrier.

Very large digital systems can contain billions of semiconductor devices and several hundred chips, all of which must be connected together. For example the IBM eServer z990 [1, 2], which was introduced in June of 2003, is based on a modular design that enables the customer to expand the system by plugging "blades" into a common back panel. Each blade contains several processor cores on a multi-chip module (MCM), up to 64 GB of memory on two memory cards and up to 12 input cables. Each of the MCM's contains 16 chips, which dissipate up to 800 W of power (heat). A total of 55,000 C4 connections[1] are necessary to electrically connect the silicon chips within each MCM used in a blade. The length of the electrical pathways used for the connections in the MCM is 378 m. In addition to the C4 connections to the chips, a complete system consisting of four blades employs a variety of connectors with a total pin count of 44,032. A photograph illustrating the advanced technology incorporated in a multi-chip-module used in a high performance server is illustrated in Fig. 1.4.

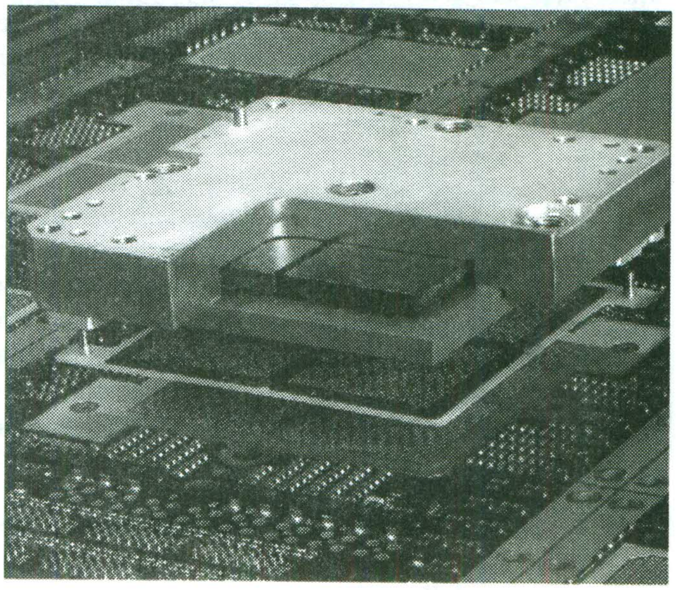

Fig. 1.4 Several levels of inter connections are illustrated in this cut away view of a multi-chip module.

Clearly the task of connecting a lead or a wire from point A to point B becomes extremely difficult when we must consider up to 100,000 wiring points and several thousand pins on either connectors or components. In addition, and even more important, is the reliability of the connections. If even one of them fails over the life of the product, the entire board will fail and the system may malfunction. With the number of solder joints exceeding several thousand in even very simple systems, meticulous attention must be given to every aspect of the design and manufacture of the connection system.

1.4.2 Thermal Management

Heat is generated at several locations in electronic systems. The power supplies, where the AC line voltage is converted to the various DC supply voltages required, are significant sources of the heat generation because of the relatively low efficiency of the AC/DC conversion process. Also, the Ohmic (I^2R) losses which occur at each chip and along the wiring result in additional heat generation. The heat load to be dissipated depends to a significant degree on the type of product. For high performance computers and signal processors, the heat load is large and elaborate cooling methods are employed. In

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[1] C4 is a term used to designate controlled-collapse chip connection, a flip chip solder joint technology which will be described in more detail in Chapter 4.

small relatively simple systems the heat generated is small and natural or free convection is often sufficient to transfer the heat from the system to the environment. In moderate sized systems, fans are employed to enhance air-cooling. Regardless of the complexity, the heat management system employed is extremely important because this system controls the temperatures of the microcircuits on the chips. These chip temperatures in turn markedly affect the reliability of the electronic system.

An equation that often accurately predicts the failure rate for an individual component is the Arrhenius model given by:

$$\lambda(T_j) = A + Be^{-C[1/T_j - 1/T_0]} \tag{1.1}$$

where A, B and C are constants that depend upon the chip and chip carrier technologies, and T_j and T_0 are the junction and reference temperatures, respectively in degrees Kelvin. In this terminology, the junction is the device location on the silicon chip surface. In studies of failure rate, it is common practice to introduce an acceleration factor $\boldsymbol{A}_\lambda$ that is defined by:

$$\boldsymbol{A}_\lambda = \frac{\lambda(T_j)}{\lambda(T_0)} \tag{1.2}$$

For most electronic components, the acceleration factor $\boldsymbol{A}_\lambda$ for the failure rate increases as an exponential function of the junction temperature as shown in Fig. 1.5. It is evident that it is essential to minimize the silicon die temperature to reduce the failure rate and to increase the mean time between failures for an electronic system. Examination of Fig. 1.5 shows that increasing the junction temperature from 25 to 100 °C increases the acceleration factor from 1.0 to 4.5.

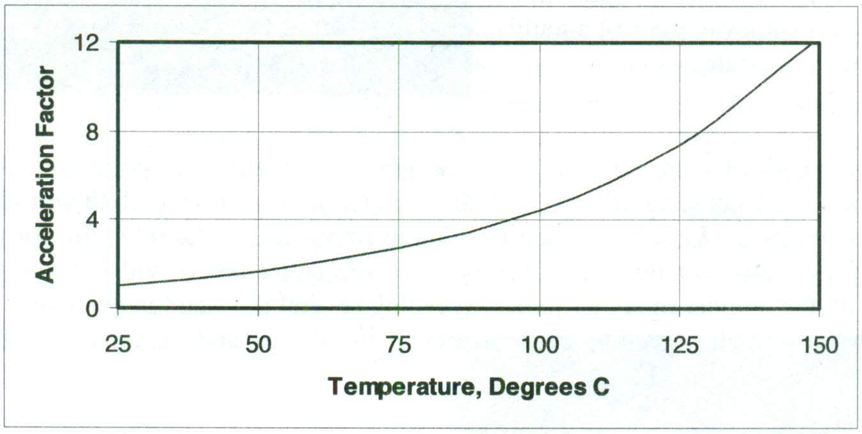

Fig. 1.5 Acceleration factor $\boldsymbol{A}_\lambda$ as a function of junction temperature showing the marked effect of temperature on failure rate.

With the very large number of components used in a typical electronic system, it is essential that the junction temperatures of the most critical of the devices be minimized to enhance reliability of the system and to improve the availability. Availability is the percent of the total time that the system remains up and operational.

The methods of cooling used in design depend upon the product price and performance. For simple low cost systems with small heat loads (for example a typical facsimile machine), the power is dissipated with natural convection, and no additional costs are involved. For slightly more complex systems with higher packing densities and higher heat loads, small fans are employed to give the improved heat transfer coefficients associated with forced convection. As we move up the price and performance scale, conduction cooling is employed where chilled water or a refrigerant is used in cold plates to transfer the heat to the environment. The high performance IBM eServer z990 introduced earlier utilizes a hybrid system with air cooling (fans) used to cool the memory chips and refrigerant to cool the high powered MCM modules [3].

Applications such as communication and surveillance satellites require deployment of electronic systems for extended periods of time in space. In the vacuum of space, heat transfer to the environment by convection is not possible and radiation methods must be employed for the final step in dissipating the heat.

All of these heat management systems must be designed in conjunction with an electrical system, which often requires that electrical insulation be placed in the path of the heat flow. The conflict in the electrical requirements for insulation, which are poor conductors of heat, and the mechanical requirements for good conductors make the design of an efficient heat transfer system quite challenging.

1.4.3 Cost

Costs are almost always an important parameter in the successful marketing of any product. The exceptions are in those cases where competition does not exist because of patent protection, trade secrets or sole source bidding. The product specification and the design of a system markedly affect its price. Corporate planners usually provide the product specifications as well as cost guidelines for both the product and the development. Product specifications requiring higher levels of performance will drive up costs. For example, electronic systems with increased performance will require faster more densely packed components that have been pre-screened for reliability. These will naturally cost more than low frequency more bulky components that have not been screened to eliminate the infant-mortality type of failures.

Production costs also depend upon the design of the PCBs, selection of connectors and cabling, and the type of enclosure used to house the electronics. Clearly many design trade-offs are made as the product is developed that affect the cost. It is important that costs of the PCBs, which depend largely on the number of layers required for signal and power wiring, and the costs of the connectors be minimized. Finally, assembly costs, which include insertion and placement of component as well as soldering operations, must be minimized.

The volume of product to be produced is a very important parameter. With high volume products, such as the systems produced for control of automobile engines, special assembly lines can be developed that enable very high production rates to drive down the assembly costs while improving system reliability. In this case, the assembly and warranty costs are traded-off against significant tooling costs. With relatively low volume products, general purpose machines are used for insertion or placement and subsequent assembly operations. With limited production, efficiencies are lost. Also, components can be damaged in the production processes resulting in increased costs and decreased yield and reliability.

1.4.4 Performance

There are many measures of performance, and a typical electronic system performance usually is specified with several parameters. Customers of computers are usually interested in processing speed that is measured in million instructions per second (MIPS) or billion floating-point operations per second (GFLOPS). Memory chips are ranked by storage capacity measured in mega-bytes (Mb) or Giga-bytes (Gb) as well as access speed. High performance chips and their first level packages are also ranked based on their switching speeds (i.e. their rise and fall times). Circuit density is also an important factor because more transistors can be placed on a specific chip thereby increasing speed while increasing the ability of a single chip to perform more functions. Circuit density also reduces the number of chips required in the design of a product, which in turn reduces cost of higher level packages.

A measure of circuit density is the I/O count, with higher counts for chips with dense circuits and larger areas. Improvements in performance coincide with I/O count. There has been a marked increase in I/O count over the last 40 years as indicated in Fig. 1.6. Single chips with I/O counts of several thousand are used in high performance systems. Multi-chip modules with I/O counts exceeding tens of thousands are also employed.

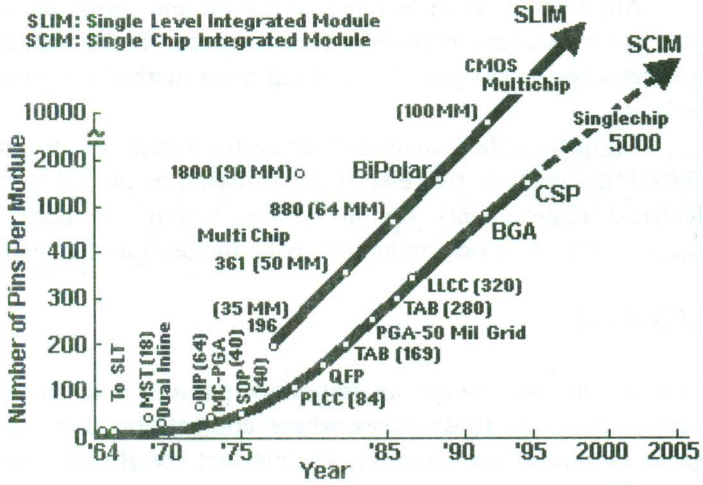

Fig. 1.6 I/O count increasing with respect to time resulting in enhanced system performance.

Thermal performance involves the ability of the thermal management system to dissipate the heat generated by the power supplies and the circuitry while maintaining the junction temperatures on the chip at specified values. Several strategies briefly described in Section 1.4.2 are employed to enhance thermal performance. Thermal performance is critically important because it markedly affects reliability and system availability.

Mechanical performance involves the ability of the product to withstand various loads during both shipment and operation. In systems with changing temperature, thermo-mechanical strains will result in the various materials of the assembly due to mismatches in the thermal expansion coefficients. This effect is of most concern in solder joints, where fatigue damage can lead to interconnect failures. For office and home entertainment equipment, vibration and shock are primarily encountered in shipping. However, for military equipment, shock and vibration conditions can be severe during normal use. Special design of higher level packaging is necessary to insure that the equipment operates without interruption during the vibratory disturbances. Other performance requirements for electronic systems designed for military and factory applications include the need for enclosures that protect the equipment from dust, humidity, large temperature variations and electric fields. Clearly, performance, whether electrical, thermal or mechanical, presents a significant challenge in designing cutting edge products that can compete in a global market.

1.4.5 Manufacturing

We noted in Fig 1.2 that mechanical development and operations which includes manufacturing are usually two separate organizations. However, the design of a product crosses all of the organizational interfaces. It is particularly important that the design of each sub-assembly in a product be accomplished so that it is compatible with each step in the manufacturing process. This is much more difficult to achieve than might be imagined, because many designers have little experience in manufacturing and many manufacturing engineers have never designed a product.

An obvious example of design for manufacturing is the use of common first level packages on a circuit board. First level packages (chip carriers) are available with several different types of lead structures such as pin in hole, gull wing surface mount, J lead surface mount, leadless, ball grid arrays, etc. An example of a chip carrier showing the chip, its wire bonds, leads and encapsulation is presented in Fig. 1.7. If different types of chip carriers are used on the same circuit board, the manufacturing process becomes much more difficult. Each type of component can require different assembly equipment or additional accessories (part feeders) for a single piece of equipment. Also, different soldering equipment and/or procedures can be required so that the circuit board might have to pass through several different assembly machines or even different assembly lines to complete the manufacturing process. These added processing steps are certain to increase cost, decrease yield and degrade the quality of the board.

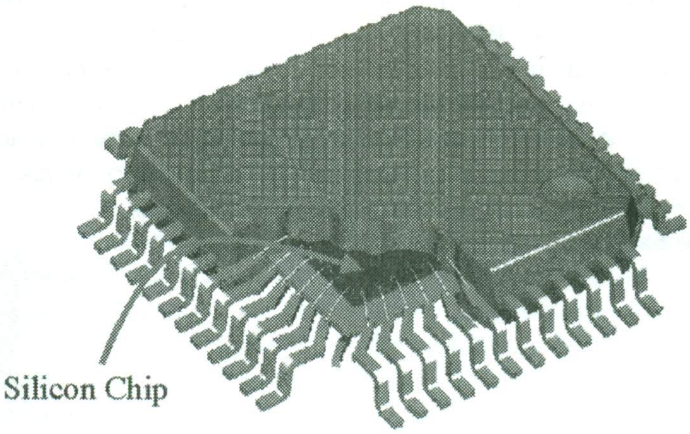

Fig. 1.7 Cut away view of a gull-wing chip carrier.

Layout details represent another example of design for manufacturing. Are the first level packages placed on the PCB with the same orientation and with sufficient space between the packages? The orientation is important as some placement tools cannot rotate a component prior to insertion or placement. If the orientation is not consistent, it could be necessary to rotate the board and this requires a second pass through the placement machine. When sufficient space is not provided between the chip carriers, the placement tools on the assembly machine can interfere with adjacent components so that assembly is impossible. In this case it is necessary to redesign the circuit board.

Dimensioning is another area that affects manufacturing in a significant way. Drawings should be dimensioned to accommodate the user. For example, the drawing of a frame which supports a circuit card during assembly, should be prepared and dimensioned for a tool maker who is responsible for the dies used to fabricate the frame. A second drawing should be prepared and dimensioned for the inspector who will certify the dimensional accuracy of the parts after they are produced. The dimensioning on these two drawings will be different so as to facilitate the tasks of the tool maker and the inspector.

Examples of design for manufacturing are numerous and they all illustrate that close cooperation between manufacturing, operations and mechanical development is essential if a high quality and cost effective electronic system is to be produced on schedule.

1.4.6 Maintenance

Mechanical design markedly affects the ability to properly service a product in the field. This is particularly important for a surprisingly large number of different types of electronic systems. Have you ever been in line in a large retail store when its computer went down? How long did you wait for it to become operational? Failures will occur at random when the reliability of the system is not adequate. To minimize delay and inconvenience, prompt service is essential. Prompt service is no accident and minimizing down time requires careful design, extensive training of service personnel, and an adequate inventory of spare parts.

The general design approach to quality maintenance is to design the system with a number of different field replaceable units (FRU's). These may be PCB's or power supplies or other sub-assemblies. One does not attempt to repair a single component that failed because it takes too long to find the flawed component, and the number of spare parts required for field service is too large to be practical. Time to access the FRU is important and that time is often controlled by the mechanical design. In the chassis of a complex computing system, drawers which open to expose banks of PCB's are often employed to reduce access time to a minimum. Extraction and insertion forces for the PCB are also important. The average service person can exert about 35 lb in engaging the edge card connector on the PCB into its contacts on the back panel. At about 6 oz/pin for edge connectors one is limited to about 100 pins before it becomes necessary to incorporate some form of assist (lever and/or jack screws) to aid the service personnel in extracting and inserting the cards.

An example of a field replaceable unit is the automotive engine control module presented in Fig. 1.8. If this unit fails it is replaced and returned to the manufacturer for repair. Replacement is simple because only three bolts are removed and then the module is unplugged.

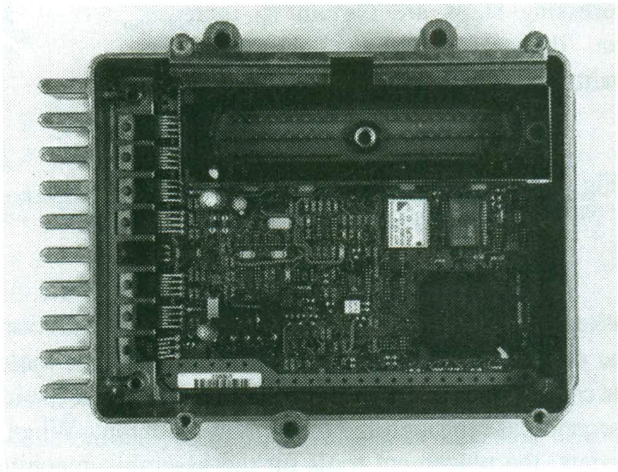

Fig. 1.8 Electronic module from an under the hood automotive application. Note that the cover has been removed to display the internal components and the circuit card.

Cable wiring is another area where long and unacceptable delays are frequently encountered in servicing. Cable harnesses often contain hundreds of wires which lead from one difficult to access location to another (see Fig. 1.9). After finding the failed cable, the service person does not want to take the time to cut the faulty cable from the harness, replace it, and then retie the harness. Instead, the design should incorporate several spare wires which can be used as substitutes to facilitate repair. In this case, repair consists of disconnecting the ends of the faulty wire and reconnecting the ends of one of the available spare wires.

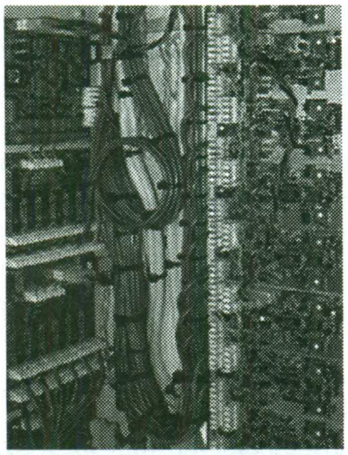

Fig. 1.9 Cable harness for both power and signal wiring in a full height electronic enclosure.

Thermal warning systems are another area of design for maintenance. When forced convection or conduction methods are used to cool an electronic system, failure of a fan, pump or refrigeration unit is possible. This failure can result in over heating of major portions of the system within a short period of time. To prevent the resulting damage, a thermal warning system, which alerts the operator to initiate a controlled shutdown, is incorporated into the system. For example, all modern personal computers employ temperature sensors on the main central processing unit (CPU) chip. Another automatic system that can be incorporated initiates an uncontrolled shutdown in the event of operator error. These safety systems should be installed on high-performance highly-priced products.

Other examples could be cited to illustrate the importance of designing the enclosures, drawers, cages and racks in the system to permit rapid and complete servicing. Close cooperation between mechanical development and the field service organization is essential during the design process to insure a product capable of quality servicing.

1.4.7 Thermo-Mechanical Deformations

Perhaps the most important mechanical problem in the design of electronic systems is the generation of strains in the solder joints due to temperature changes that occur in shipping, storage, and operation. The chip carriers are soldered to printed circuit boards to mount them mechanically and to connect them electrically. Unfortunately there is often a large mismatch in the effective coefficient of thermal expansion between the chip carrier and the printed circuit board. The coefficient of thermal expansion of the PCB is higher than that of the chip carrier ($\alpha_{PCB} > \alpha_{cc}$). As a consequence, temperature changes ΔT produce a differential expansion d (or contraction) as illustrated in the simplified/idealized chip carrier geometry shown in Fig. 1.10. This differential expansion (or contraction) produces a shearing strain γ in the solder joints that can be estimated by the expression:

$$\gamma = \frac{L(\alpha_{PCB} - \alpha_{cc})\Delta T}{2h} \tag{1.3}$$

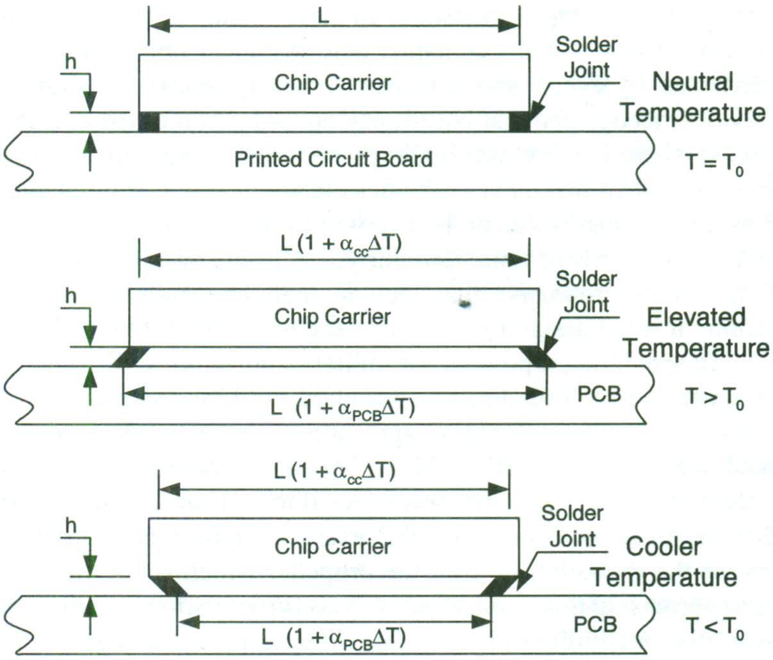

Fig. 1.10 Two-dimensional schematic showing expansion and contraction of a chip carrier and a PCB due to temperature changes and a mismatch in coefficient of thermal expansion.

Electronic systems can undergo hundreds or thousands of start-up and shut-down cycles over their lifetime. The temperature of the components increases after start-up and decreases after shut-down. For this reason, the solder joints are subjected to cyclic thermal shear strains that can result in thermal fatigue failure of the solder joints. An example of a failed solder ball joint found on a flip chip type chip carrier is presented in Fig. 1.11. The fatigue crack typically initiates after hundreds of thermal cycles, and it then grows slowly until the crack crosses the joint and failure occurs.

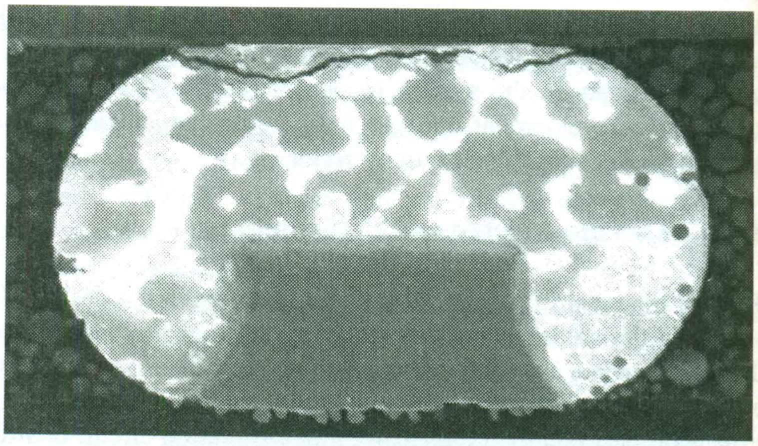

Fig. 1.11 Fatigue crack developed in a solder ball type solder joint of a flip chip package.

1.4.8 Shock and Vibration

Shock and vibration are important at three different times in the life of an electronic system. The first occurs during the manufacturing and assembly process, when the product or its sub assemblies are being moved from one manufacturing station to another. Abusive handling or dropping the product can produce very high accelerations (shock loadings), which will deform or fracture devices and cause failure of the system to function. The second occurs in transporting the system through the distribution chain until it is finally installed at the customer's location. If the distribution chain is long, the product will be handled at several locations. In these situations, the normal approach is to enclose the product in a shock proof box. Such a container deforms under impact when the product is dropped, and limits the accelerations (g-levels) and transient forces (g-loads) transmitted through the box to the product. Finally, it is recognized that both shock and vibration environments may be encountered in service. Of course, in typical office surroundings a computer system is not subjected to adverse environments. However, modern handheld consumer electronics (e.g. cellular phones and portable music players) as well as military hardware can be exposed to severe vibrations and or shocks on repeated occasions and for extended periods of time. Similarly, electronic systems for automotive applications are subjected to very hostile environments that include high temperature, dust, humidity in addition to shock and vibration. It is the design for such hostile environments that will be covered in this textbook.

In specifying a product for military applications, the procuring agency will define the vibratory environment through the use of a standard military specification. For example, ship board electronic systems intended for submarine applications are often designed to satisfy the vibration specification defined in MIL-STANDARD 167-1. This mil-standard describes the g-levels and frequencies to which the electronic equipment must be subjected to and survive during qualification tests, as indicated in Fig. 1.12. The frequency range for shipboard equipment is relatively low 4-34 Hz, because the primary source of the excitation is from the propeller which rotates at a relatively low angular velocity. The design approach in this application is to construct stiff structures with relatively high natural frequencies to avoid the possibility of a resonance frequency occurring in the cabinet, any circuit board or major sub-assembly within the frequency range specified.

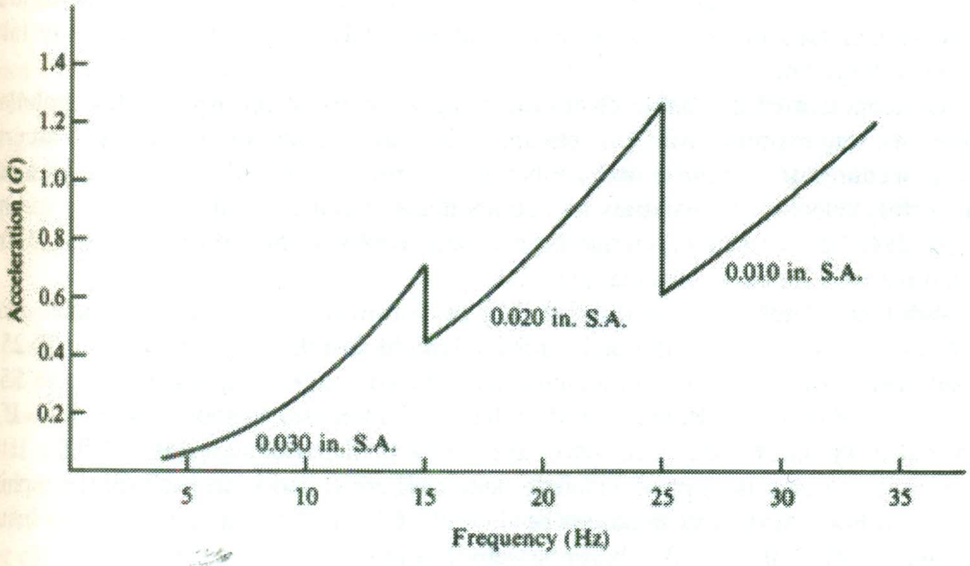

Fig. 1.12 Vibration specification from MIL-STD-167-1 for equipment installed on naval vessels.

The specifications on the vibratory environment for aircraft electronics are entirely different. The range of frequencies is much wider—from 15-2000 Hz. Moreover, with the weight limitations imposed on aircraft electronics, it is impossible to design the enclosures and PCBs with sufficient rigidity to avoid resonances. For this reason, the design approach is to accept resonances and limit the force and displacement transmission factors. With limited forces it is then possible to design the circuit boards and sub-assemblies with sufficient fatigue endurance to avoid failure during extended periods of exposure.

Upon completion of the prototype of a system, it is subjected to a closely controlled qualification testing where the prototype is exposed to a specified shock or vibration environment. Damage that often occurs includes fatigue of structural components which support the electronic sub assemblies; wiring, cable and solder joint failures due to fatigue; pin breakage in connectors; cable chafing; and shear of bolts and pins due to shock imposed loads. Clearly the design of military, automotive and factory hardware with demanding shock and/or vibration specifications is a challenging problem which requires an extensive knowledge of this subject. We will show the basics of the theory covering shock, vibration and fatigue in treating this area of design.

1.4.9 Reliability

System reliability is measured by the ability of a system to meet its specification for an extended period of time without failure. The reliability of a system is affected by both hardware and software because either can fail. If your computer crashes, the software has failed and it is necessary to reboot your computer or to reload an application program. Usually this is not a serious issue if the delay is short and only one person is affected. However, if the accounting system of a major bank crashes, hundreds of people standing in line have to wait for their accounts to be serviced. While system failures (crashes) due to software are more frequent, failures due to hardware problems are more serious. It takes much more time to locate and replace a faulty circuit board or failing connector than to reboot a system. In this textbook, we will focus on hardware issues that affect reliability.

Reliability controls system availability, which is critically important for many applications including airline reservation systems, bank account management systems, communication systems, health care systems, air traffic management, etc. In many applications, redundant systems are employed so that if one system fails the back-up system is automatically activated to seamlessly take over the tasks of the primary system.

The development of a reliable electronic system entails many aspects that include designing against failure, insuring manufacturing process are under statistical quality control, and ascertaining that maintenance procedures are adequate and are being performed on schedule. To design against failure requires the correct selection of materials and components, careful layout of the PCB and selection of connectors, the development of an effective heat management system and the selection of an enclosure that provides protection for environmental parameters.

Reliability also affects cost, as illustrated by the following hypothetical example. An integrated circuit (IC) that fails a test on the wafer and is rejected might cost the chip maker about $0.25. If that IC is detected as flawed after it is placed in a chip carrier the cost to the chip maker is about $5 to $10. If the flawed IC is found on the PCB, the cost of replacement increases to about $20 to $50. If the flawed IC is discovered in system testing, the cost of replacement increases to $200 to $500. If the flaw is discovered after the product is shipped and field personnel are called in to perform the repair, the costs are in the neighborhood of several hundreds of dollars. Clearly, it is cost effective to insure that the components and materials are flaw free before assembly and shipment of a product.

Problem areas affecting reliability such as solder joint failures are studied by using analytical, computational and experimental methods. An example of such a study is presented in Fig. 1.13, which shows a solder joint failure that occurred in a thermal cycling test of a ceramic chip resistor mounted on a metal-backed glass-epoxy composite printed circuit board. A finite element model of the solder joint, the ceramic resistor and the PCB was also developed. The prediction of the finite element model for the distribution of the plastic shearing strains in the solder joint is shown in Fig. 1.14. The results from the test program and the analysis employing the finite element model were in close correspondence.

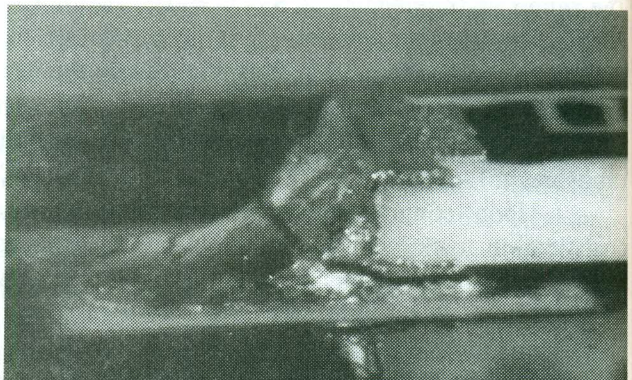

Fig. 1.13 Solder joint failure of a ceramic resistor due to thermal cycling.

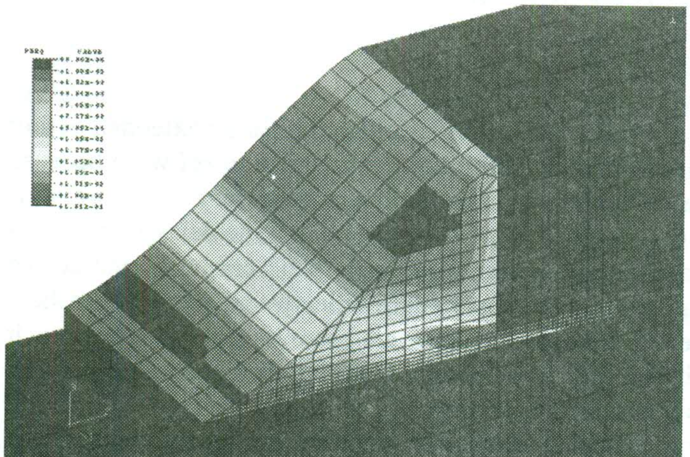

Fig. 1.14 Results from a finite element analysis showing the shearing strain distribution due to a mismatch in the temperature induced thermal expansion of the ceramic resistor and the PCB.

1.4.10 Ergonomics

Ergonomics involves the relationship between people and the machine or in this case the electronic system. The basic idea is to design the system to reduce the physical effort required by the operator when using the system. Examples of ergonomics in design of electronic systems are numerous. The design of a keyboard for a computer terminal should clearly take into account the need for concave key shape with tactile feedback. Spacing between the keys, the angle of the keyboard, the ability to change this angle and the height of the keyboard all affect the productivity of the operator and the quality of the output.

There are three main areas of ergonomics which markedly affect mechanical design—the operator panel layout, the operator workstation and the environment. The environment pertains to the office, vehicle or factory and includes noise, lighting and temperature. Layout involves placing switches, meters, lights, and control knobs in logical positions where the operator's task is made as easy as possible. For example, the meter which displays the state of a variable should be located adjacent to the control knob for that variable. This placement permits the operator to monitor the meter as the control knob adjustment is made. Controls should follow common convention--clockwise to increase voltage or current. Switches toggle upward in the on position in the US, but remember that they toggle downward for the on position if the product is designed for a customer in Europe.

Workstation design involves operator comfort and is much more important than generally considered, particularly if the operator is expected to be on station for extended periods of time. If possible, the operator should be comfortably seated as it increases his or her attention span and alertness. The chair should be designed with sufficient adjustments to adapt to the user and not vice-versa. While mechanical designers may not have the responsibility for designing chairs, they should be sufficiently knowledgeable in anthropometrics to select an appropriate chair and then to design the operator-machine interface to accommodate the range in the size and weight of the operators which will occupy that chair. An example of a workstation design for a computer operator is illustrated in Fig. 1.15. Note the dimensions indicating the position of the monitor relative to the eyes of the operator, the height of the table and chair and the position and tilt of the keyboard.

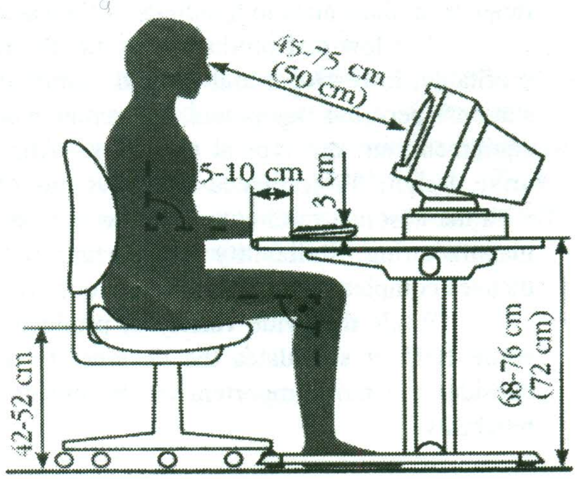

Fig. 1.15 Important dimensions in the design of a workstation for a computer operator.

The office, factory or vehicle environment involves noise, lighting and temperature. Noise can be very distracting and prevent complete concentration on the task at hand. If the noise is sufficiently loud and the operator is exposed for extended periods of time, hearing losses and other physical disorders result. Lighting involves the proper intensity and distribution of light at the work station. Of particular importance is glare from instrument panels and displays such as CRT's. Glare can be avoided by the use of anti-reflection coatings or by the positioning of the light sources to avoid the reflections producing glare. When glare is permitted, displays cannot be monitored with out eye strain and/or error. Temperatures either too high or too low result in discomfort and dissatisfaction of the operator. Clearly sweating or shivering operators are less effective and efficient.

1.5 RANGE OF PRODUCTS

The products produced and marketed as electronic systems cover an extremely wide range. Some products are advanced, complex and high in price. Others are very simple, produced in millions of units and very competitive in cost. These differences in the price and volume of the products require a change in the design approach and in some cases major changes in the methods employed.

At the risk of over simplification, we will divide the entire market of electronic products into three general classes, namely the high-end, intermediate- and low-end products. As the name implies, the high-end products are high-performance, high-cost, long-life systems usually produced in relatively low volume. The primary design objective with the high-end product is performance, and while cost is also important, it is secondary to performance. Large mainframe computers, supercomputers, massive servers and advanced signal processors for military applications are products in this category. Extremely high reliability, often achieved with redundant sub-systems, is a characteristic of these products. Prices are often above one million dollars per unit with a relatively low volume of unit sales. Select laboratory instrumentation usually associated with health care facilities or major national laboratories also fall into this category.

The intermediate product line is much broader with lower cost products included in this category. Mid size computers, less critical military systems, most laboratory instruments and most special purpose data processing systems are the typical products. Both performance and cost are quite important. Any gain in performance must be carefully balanced by the extra expenditure required to achieve the incremental gain in speed or reliability. Product volume is larger, and hence the design is coordinated even more closely with manufacturing. The product life is in the intermediate range so the design tends toward a flexibility that permits product upgrades by making periodic changes in the model. Reliability remains important but usually not at the cost of major redundant sub-systems. Prices usually range from thousands to hundreds of thousands of dollars per unit in the intermediate range product.

The low-end product is by far the largest segment of the market, the most competitive, least profitable, lowest cost and most demanding from the design point of view. Products such as work stations, personal computers, consumer electronics, automobile electronics, home appliances, office equipment, etc. are typical examples. Annual product volume is very high and manufacturing costs drive design. Performance is always important, but in these products performance must be achieved with the absolute minimum increase in cost. Quality is achieved by the close coupling of design and manufacturing. Reliability is important, but often this design goal is supplemented with a policy that dictates complete replacement of the unit for a day or more during servicing.

While this wide variety of products complicates the task of writing a textbook to address the entire field, it stimulates the designer to address development in a market-oriented manner and to consider the most important of the essential design characteristics—quality, cost, performance and reliability.

1.6 BUSINESS ASPECTS

The electronics system business is and has been the fastest growing segment of the manufacturing and service industries in the US during the past forty years. Annual sales, depending upon the definitions imposed, are in the neighborhood of about a trillion dollars per year and growing at an annual rate of nearly 10%. It is a very competitive business because it requires relatively little capital[2] to introduce a new product and to start a new company. Also, funds may be provided by venture capitalists seeking to share the equity in the firm. New ideas for new products are essential. The successful ideas and products developed by existing and/or new companies drive the growth in the industry.

[2] Many small business can be started with an initial investment of $10 to 20 million.

Paramount to the growth of the business has been the technological advances which seem to occur on a schedule similar to the development of new and advanced integrated circuits (IC's). This progress, illustrated in Fig. 1.16, shows the steady increase in the number of transistors which can be placed on the small area of a silicon chip. As more and more devices and circuits are placed on a single chip, several advantages result which permit the development of entirely new products and the marked improvement of existing products. For example, each new generation of memory chips includes more memory capacity in the same or smaller physical area, with the same or lower cost. Also, as chips become increasingly dense, the speed of the switching is improved and the processing rate of the product increases.

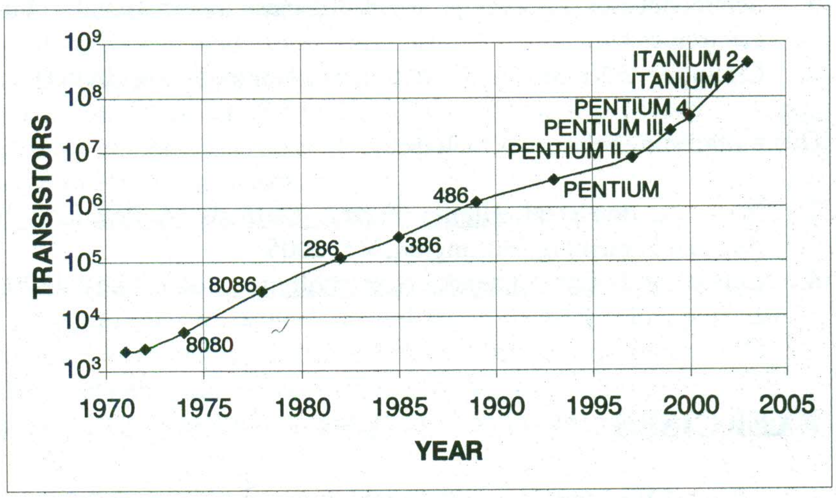

Fig. 1.16 Continuing progress made in increasing the number of transistors on a single chip. Data from Intel.

We are experiencing a rapidly changing business world that is driven by new developments in IC technology, by new ideas for product development, by new requirements for information processing on the Internet, and by Global facilities for research, development and manufacturing. Consider the rapid changes occurring in products introduced in the last decade such as DVD players and writers, cellular phones, digital cameras, hard drive recorders (TiVo), and portable music players (iPod). These developments will lead to improvements in the way we process and store information, and will provide the basis for continuous enhancement in the standard of living for society as a whole.

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The following periodicals provide current articles which will aid you in understanding the acronyms and in identifying the issues involved in mechanical design of electronic systems:

1. IBM Journal of Research and Development, International Business Machine Corporation, Armonk, NY.
2. Electronic Design, Penton Media, Inc. find it online at http://www.elecdesign.com.
3. Surface Mount Technology (SMT), Penn Well Corp. Find it on line at http://www.pennnet.com.
4. Printed Circuit Design and Manufacture, UP Media Group, Find it on line at http://www.pcdandm.com.
5. Semiconductor Packaging, Reed Business International, Find it on line at http://www.read-electronics.com.
6. Circuitree, BNP Media. Find it on line at http://www.circuiTree.com.

Other interesting references include:

7. N. A. Stanton et al, Human Factors Methods: A Practical Guide for Engineering and Design, Ashgate Publishing, Burlington, VT, 2005.
8. Cunniff, P. F. Environmental Noise Pollution, John Wiley, 1979.

EXERCISES

1.1 Inspect the computer system which you use most of the time. Describe the key board features which help you type more accurately and those features which help you from becoming tired as you type. What do you think of the keyboard layout? Is it optimized in any sense? Clearly it is not, but do you know the story behind why the keyboard layout is so poor.

1.2 Why are some of the lead wires to your PC placed on the rear panel instead of on the front panel where they would be more accessible? Why are these leads placed in a location which is not easily accessible?

1.3 Why are the vents for the cooling air placed on a side or back panel of your PC? The top of the PC provides a larger area and would permit including more vents for enhanced air flow with a lower head loss. Please explain this apparent conflict in the placement of the vents.

1.4 The sound pressure level issued by a product is measured in decibels. What is the typical sound pressure level produced by a rock and roll band? This is clearly too high for any product, but what are acceptable sound pressure levels? What common product usually exceeds the acceptable limits in an office environment?

1.5 List the different types of connectors with which you are familiar.

1.6 Take the cover off of your PC and identify as many of the sub-assemblies as possible.

1.7 Without removing a circuit card identify as many of the components on that card as possible. If you don't follow these instructions and you do remove the card for a better view make sure you wear a grounding strap on your wrist. The strap will prevent electrostatic damage to one or more of the components.

1.8 Estimate the number of solder joints and pins for connections on this PC circuit card.

1.9 Describe the thermal management system in five different electronic products which you encounter on a day to day basis.

1.10 Prepare a graph of the failure rate, as a function of junction temperature for T_j ranging from 20 to 150 °C. Let A = B = C = 1 for this initial determination. Discuss the effect of the higher temperatures on the failure rate.

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1. IBM Journal of Research and Development, International Business Machine Corporation, Armonk, NY.
2. Electronic Design, Penton Media, Inc. find it online at http://www.elecdesign.com.
3. Surface Mount Technology (SMT), Penn Well Corp. Find it on line at http://www.pennnet.com.
4. Printed Circuit Design and Manufacture, UP Media Group, Find it on line at http://www.pcdandm.com.
5. Semiconductor Packaging, Reed Business International, Find it on line at http://www.read-electronics.com.
6. Circuitree, BNP Media. Find it on line at http://www.circuiTree.com.

Other interesting references include:

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1.11 Give an example of good design for manufacturing of an electronic product. If you can't think of one for an electronic product, give an example for an automotive product.

1.12 Derive an equation for the shearing strain in a solder joint due to temperature changes. Reference Fig. 1.9 for drawings of the chip carrier and definition of the symbols.

1.13 Give an example of poor design for manufacturing for electronic products.

1.14 If you drop a box on the floor from say a height of 1.2 m, determine the deceleration during impact. What assumptions did you have to make in your analysis?

1.15 What is your opinion of the ergonomics design of the chair in your office or your class room? Why do you think management selected the chair you used?

1.16 Give an example of a high-end product and estimate its cost.

1.17 Give an example of an intermediate product and estimate its cost.

1.18 Give an example of a low-end product and estimate its cost.

1.19 What is the least expensive electronic product that you can identify? Is it produced in a large volume? How many electronic components does it contain? Is it designed for ease of manufacturing? Is it designed for ease of maintenance?

1.20 What is a venture capitalist? Do they serve an important function in the development of small business in the US?

1.21 Samsung Electronics, a world leader in advanced memory technology, announced in December of 2004 that it has developed a 512Mb DRAM device. It will begin to market this high density memory chip in 2005. Samsung introduced the 256 Mb DRAM chip in November of 2003. . When do you estimate that they will announce the development of the 1 Gb memory chip?

1.22 If your PC memory card contains 1 Gb how many memory chips are installed on the board if the chips are:

(a) 64 Mb
(b) 128 Mb
(c) 256 Mb
(d) 512 Mb