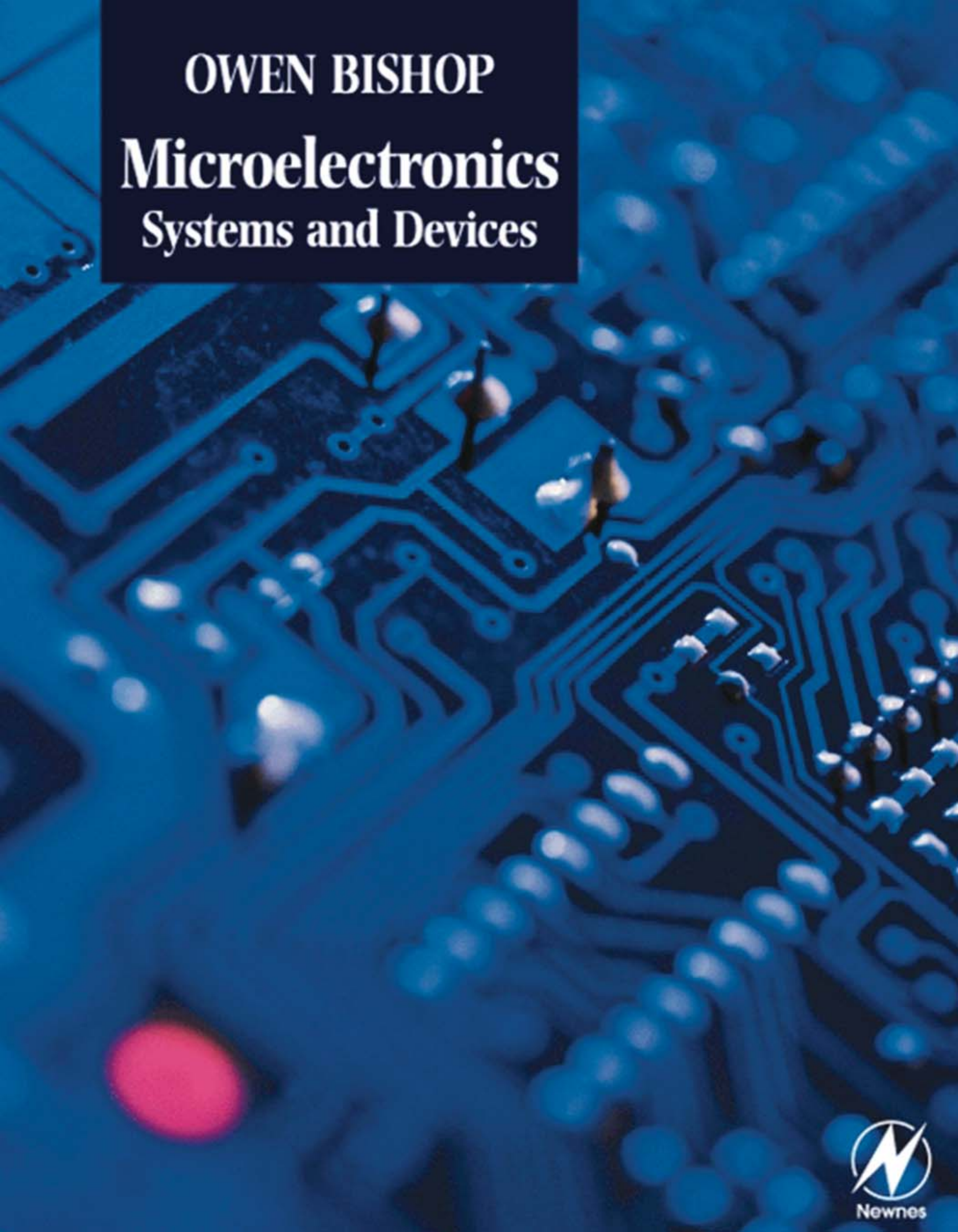
OWEN BISHOP

Microelectronics

Systems and Devices



Newnes

Microelectronics – Systems and Devices

This Page Intentionally Left Blank

Microelectronics – Systems and Devices

Owen Bishop

Newnes

OXFORD AUCKLAND BOSTON JOHANNESBURG MELBOURNE NEW DELHI

Newnes
An imprint of Butterworth-Heinemann
Linacre House, Jordan Hill, Oxford OX2 8DP
225 Wildwood Avenue, Woburn, MA 01801-2041
A division of Reed Educacational and Professonal Publishing Ltd

A member of the Reed Elsevier plc group

First published 2000

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN 0 7506 4723 X

Printed and bound in Great Britain

Contents

Preface

This book is written for a wide range of pre-degree courses in Microelectronic Systems. The contents have been carefully matched to current UK syllabuses at Level 3, but the topics covered, depth of coverage, and student activities have been designed so that the resulting book will be a student-focused text suitable for the majority of courses at pre-degree level around the world. The only prior knowledge assumed is basic maths and science.

The UK courses covered by this text are:

- Advanced GNVQ Units in Microelectronic Systems from Edexcel
- BTEC National units in Microprocessor systems, Micro-Electronic Systems, and Software Design Methods.

Essential theory is provided here but the book is strongly practical in its approach, encouraging students to assemble and test real microelectronic systems in the laboratory. The examination syllabuses do not specify which processors and which programming languages the student should cover. The suppliers' catalogues list several hundred microprocessors and microcontrollers and any one or more of these could be selected as a subject for study. There is likewise a variety of languages or versions of languages that may be used to program them. To keep the size of the book within reasonable bounds, the book looks at the Zilog Z80 as a typical microprocessor, and at the Atmel AT90S1200 as a typical microcontroller. Both of these are readily available from the major suppliers such as Farnell, RS Components and Maplin, as well as from several of the smaller firms. Other processors are mentioned where they show interesting differences from these two types. With regard to languages, the book concentrates on assembler (for the Atmel controller), BASIC and PBASIC (for the Stamp). Other languages are described, including C.

The descriptions of these processors and languages are intended to exemplify processors and languages in general. They are aimed at giving the student a wide view of the topic, but it is not expected that students will centre their studies on these particular processors or languages. In keeping with the syllabuses, the book leaves the student with an unrestricted choice of devices, prototyping systems and programming languages.

The book is a study guide, suitable for class use and also for self-instruction. The main text is backed up by boxed-off discussions and summaries, which the student may read or ignore, as appropriate.

There are frequent ‘Test Your Knowledge’ questions in the margins with answers given at the end of the book. Another feature of the book is the placing of short ‘memos’ in the margins. These are intended to remind the student of facts recently encountered but probably not yet learnt. They also provide definitions of terms, particularly of some of the useful jargon associated with microelectronics and computing.

Each chapter ends with a batch of examination-type questions, and in most instances with a selection of multiple choice questions. Answers to the multiple choice questions appear at the end of the book.

Owen Bishop

This Page Intentionally Left Blank

Part A – The Hardware

1 Systems in action

Summary

The essential features of a microelectronic system are described. These are illustrated by descriptions of typical systems: a cordless telephone, programmable logic controllers in industry, a personal computer, measuring instruments and data loggers, the control room of a power station, and distributed processing in flight control of aeroplanes.

Digital: a digital quantity (often a voltage) takes *either one* of two values. Contrast this with an *analogue* quantity (often a voltage), which takes *any* value within a given range.

Integrated circuit: one that is built up from a large number of components connected together on the same chip and contained in a single package. The term 'integrated circuit' is shortened to 'IC in this book.

Program: a series of instructions telling the CPU what to do.

Microelectronic systems are *digital* systems, built from one or more *integrated circuits*. They contain a *central processing unit* (CPU) which is *programmed* to make the system perform its tasks. The CPU is either a microprocessor or a microcontroller or, in complex systems, there may be more than one. Microelectronic systems are widely used in equipment and installations such as washing machines, automatic teller machines, personal computers, production line packaging machines, printing presses and radio-telescopes.

The CPU has such complicated tasks to perform that is is made up of hundreds of thousands or even millions of transistors, as well as resistors and other components, all assembled on the same silicon chip. There are two main types of CPU:

- Microprocessors
- Microcontrollers.

These have much in common, although there are important differences between them. A micro*processor* is just what its name says. It is a data *processor*. It is designed to be able to *process* large quantities of complex data at high speed. It needs the support of other units, such as memory and input/output devices to make up a complete system. A micro*controller* usually operates more slowly and has less processing capability but it has the advantage of having the other units on the same chip. It is a 'computer on a chip' and, as such, is used on its own to take full *control* of a piece of equipment or installation.

Test your knowledge 1.1

What are the four key features of a microelectronic system?

Because CPUs are programmable, the behaviour of the system can be changed in many ways simply by revising the program. This gives microelectronic systems a big advantage over hardwired logical systems, such as are used in the less expensive home security systems, the older types of washing machines, and in remote control systems. Such systems may perform their intended task well but it is not easy to alter the system once it has been wired. Any major change of action usually involves rewiring, possibly changing some of the ICs and, frequently, making so many alterations that it is simpler to scrap the circuit and build a fresh one on a new circuit board. The flexibility of microelectronic systems is one of the main reasons that they are so widely used.

High and low

The two values that a digital quantity can take are often referred to as *high* and *low*. A high value represents logical high, which is equivalent to the binary digit '1'. A low value represents logical low and is equivalent to the binary digit '0'. Some systems operate with the values the other way round (negative logic) but this is very unusual.

In microelectronic circuits these values are represented by voltages. Low is often represented by 0 V, or a value fairly close to 0 V. High is often represented by +5 V, but other values may be used in other types of microelectronic system.

Note that, to a power engineer, *high* voltage means something more than mains voltage, for example 450 V, or even 132 kV. To a microelectronics engineer 'high' usually means a mere 5 V. It is slightly higher in certain kinds of system. However, high is just 3.3 V in the *low voltage* systems that are intended for portable battery powered equipment.

A survey

A simple system

Before we look in more detail at what what goes on inside a CPU, we will take a few examples of the way microelectronic systems are used in everyday life and at work. The cordless telephone is a typical example (see over). As in any other microelectronic system, the circuit centres on a CPU. In a cordless telephone this is a microcontroller, complete with memory.

It may be wondered why a cordless telephone needs a CPU, yet an old-fashioned corded telephone can operate without. One of the reasons is that the corded telephone is wired directly to the public network, but the cordless telephone has to make radio contact with its base before a call can be received or made.

The handset of a cordless telephone (Fig. 1.1) consists essentially of a radio transceiver that is under the control of a CPU. The radio has limited range and communicates with the base unit, which may be up to 200 m away, normally in the same building. The base unit

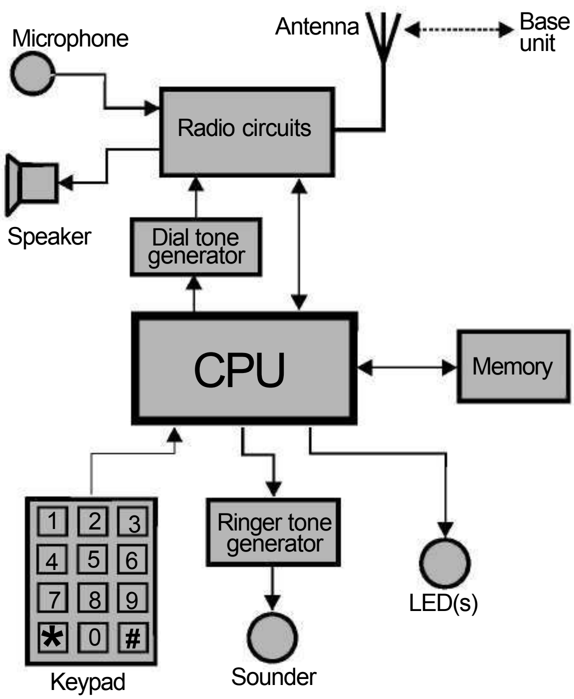


Figure 1.1 *A cordless telephone handset is under the control of its central processing unit (CPU). This may be a microprocessor or (more often) a specialised microcontroller.*

The exchange of signals (such as identity codes, 'ready to receive', 'ready to transmit') between the handset and its base station is known as *handshaking.* A similar handshaking dialogue occurs when a microcomputer communicates with a printer.

DTMF: dual tone multi-frequency dialling codes a dialled number by producing two tones at the same time, one below 1 kHz and one above 1 kHz. For example '5' is represented by a 770 Hz tone plus a 1336 Hz tone. The system codes all the numbers from 0 to 9 and also 'star' and 'hash' by using 12 different pairs of frequencies.

Cordless telephones

Fig. 1.1 shows that the radio circuits are under the direct control of the CPU.The double-headed arrow between the CPU and radio circuits indicates that signals may pass in both directions (though not both ways at exactly the same time).

The radio circuits of the base station and the handset are permanently switched on, waiting for a call. When the base station receives an incoming call from the public network, it sends out a digital signal by radio. This signal includes a code that identifies the base station. The handset receives this signal. However, it is also able to receive signals from any other base stations within range. The signal is sent to the CPU, which then checks to find out if this is the code of its own base station. If it is not, it ignores it and nothing further happens. If it is recognised, the CPU makes the radio circuit send an acknowledging signal. The signal includes a code to identify the handset. The base station has been waiting to receive this signal, which is checked by its own CPU to make sure that it comes from a handset with which it is allowed to communicate. Then the CPUs both open up the radio channels for two-way conversation between the handset and the base, and by land line to the remote caller.

The procedure is similar for an outgoing call. The CPU makes the radio circuit transmit a series of code groups, including its own identity code and the number to be dialled. On confirming that the identity of the handset is acceptable, the CPU of the base station dials the number. In practice, dialling the number means generating a sequence of pairs of DTMF tones that code the required telephone number. When the number answers, it replies to the handset and radio channels are opened for two-way conversation.

The lower part of the diagram shows the input and output that links the CPU to the user. The keypad is used to send input to the CPU to tell it what number to call. It is also used for operations such as storing frequently needed numbers in memory. The CPU has output to one or more signal LEDs that indicate when a call is in progress. It has output to a separate IC which includes an oscillator to generate the ringing tone.

communicates with the public telephone system through the subscriber's ordinary telephone line. The circuit of the base unit is similar to that of the handset in many ways.

Operating system: a program which tells the CPU how to do all the basic tasks of running the system.

The operating system is stored permanently in a part of memory when the telephone is manufactured. There is also a section of memory to hold useful data, such as the number currently being dialled and a list of frequently used telephone numbers. This data is changed from time to time by the user.

A necessary part of any microelectronic system is the squarewave generator known as the *system clock*. This provides the regular series of pulses that drive the CPU. It is not shown in Fig. 1.1 because it is usually included on the same chip as the CPU. The timing of the clock usually depends on a quartz crystal, just as in a digital watch. There is no room for the crystal itself on the CPU chip, so this is connected across a pair of terminal pins of the IC. The frequency of the crystal may be several hundred kilohertz or a few megahertz.

Test your knowledge 1.2

Why is it preferable to have a DTMF generator in the telephone handset?

Test your knowledge 1.3

What is the name given to the square wave generator that drives the CPU?

One of the essential outputs of a telephone is the ringing tone. It would be possible for the CPU to be programmed to generate this tone itself, but generating the tone would occupy the CPU at times when it could more usefully be doing something else. It is common in microelectronic systems to employ special-purpose ICs like this where there are simple repetitive tasks to be done. The telephone has another special IC to generate the DTMF dialling signal for transmission to the base station.

Cellphones have circuits similar to cordless phones, the main difference being that the cellphone communicates directly with the public system through a base station up to several kilometres distant. There is usually an LCD message screen to display numbers dialled and other useful information.

Controllers in industry

Microelectronic systems are widely used in industry. This section describes an example of microelectronic control of a chemical process (Fig 1.2) by a *programmable logic controller*, or PLC. The CPU (with system clock), its memory, keypad and display, are part of a single unit (Fig 1.3). As in the telephone, the heart of the system is a CPU. This has access to memory for storage of the program and working data. In some systems the whole memory or part of it is included on the CPU chip. There is often a keypad by which the operator runs the system, and there is a message panel on which the CPU displays information about the current state of the system.

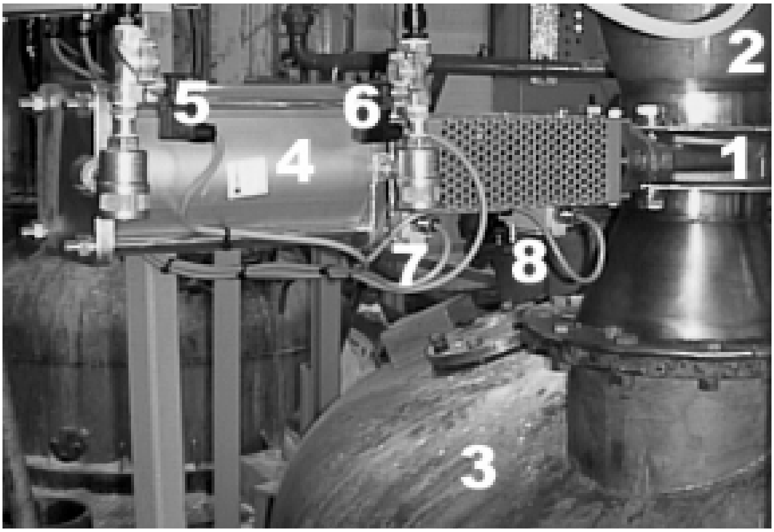


Figure 1.2 *In the manufacture of chipboard, the bonding resin is made by heating a mixture of urea and formaldehyde. A slider valve (1) controls the flow of urea from a hopper (2) to the processing kettle (3). The valve is opened or closed by a shutter that is moved by a piston enclosed in a cylinder (4). The piston is moved by admitting compressed air into the cylinder on one side of the piston or the other side. The flow of air is controlled by two solenoid-operated air valves (5 and 6), which are switched on or off by the microcontroller. Proximity sensors detect when the valve is fully open (7) or fully closed (8) and supply this information to the microcontroller.(By courtesy of Kronospan Ltd., Chirk)*

Test your knowledge 1.4
What device is at the centre of the system of a programmable logic controller?

Actuator: A device in a control system which performs an action. Examples are motors and solenoids or devices driven by motors or solenoids, such as valves.

In the cordless telephone previously described, currents are small and can usually be fed directly to the inputs of the CPU. Similarly, the outputs of the CPU can provide sufficient current at the correct voltage to drive logic circuits, including those driving display circuits and tone generators. This is rarely the case in industrial plant. Motors often operate on a 24 V DC supply or even run on alternating current at mains voltage. Similarly, signals from sensors may be at voltages higher than those acceptable by the CPU, and may sometimes be AC signals.

Interface: A circuit used for passing information between two other circuits. Examples: a modem passing digital data between a computer and the tele-phone network, an opto-isolator passing simple 'go-stop' commands between a CPU and sensors or actuators.

Industrial sites are well known for generating strong electromagnetic interference, so the input signals from sensors may carry high voltage spikes. EMI may also be picked up by the output circuits and could get back to the processor. For this reason, interface circuits (see Fig. 5.1) are needed, both on the input and output sides to provide a low-voltage, low-current, electrically 'quiet' environment in which the CPU can operate reliably.

A Seimens 95U PLC can be seen in Fig. 1.4. The PLC is wired to a number of input and output interfaces which are mounted on the rack in the cabinet. Cables run from these to the sensors and actuators on the plant. A few others run to control switches and indicator lamps on the door of the cabinet. The door is normally closed when the plant is operating, so acting as a control panel.

The program of a PLC runs continuously in a loop for as long as it is switched on. The first stages of the program read the state of each sensor and store the results in a special area of memory. Then the program examines the input data and decides what action is to be taken. As an example, take the valve mechanism of Fig. 1.2. If the proximity sensor (7) shows that a shutter has reached the far end of its travel, the valve (5) admitting compressed air to the nearer side of the cylinder must be closed. A message indicating 'close valve' is stored in the output area of memory of the PLC. When all the logical decisions have been taken and the future output state is stored in memory, the program reaches its third and final stage. It sends the stored output data to the actuators. The actuators are switched on or off in response to the latest state of the system. The program repeats immediately, so it is

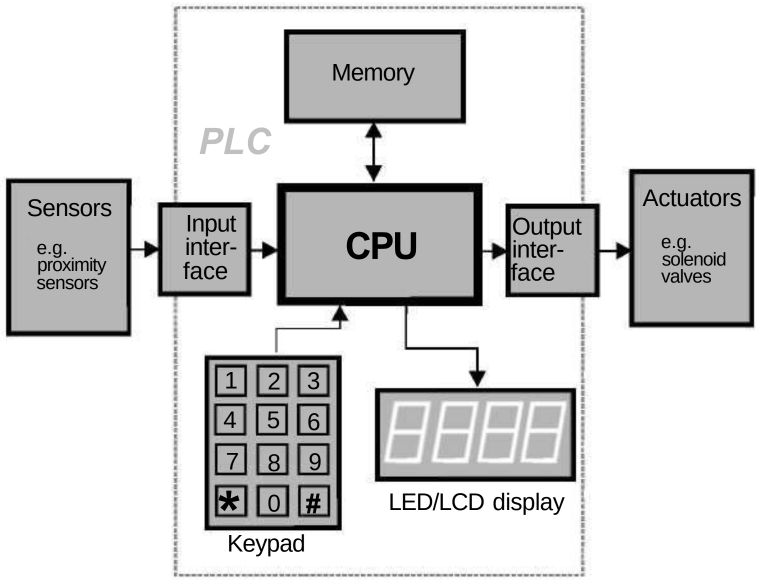


Figure 1.3 *Like almost every other control system, a PLC is centred on a CPU. The dotted line indicates that the CPU, memory, keypad and display are normally installed as a single general-purpose unit. Interfaces to sensors and actuators may be separately installed, and there may be several hundred in the system. Smaller systems may use PLCs with a dozen or so built-in interfaces.*

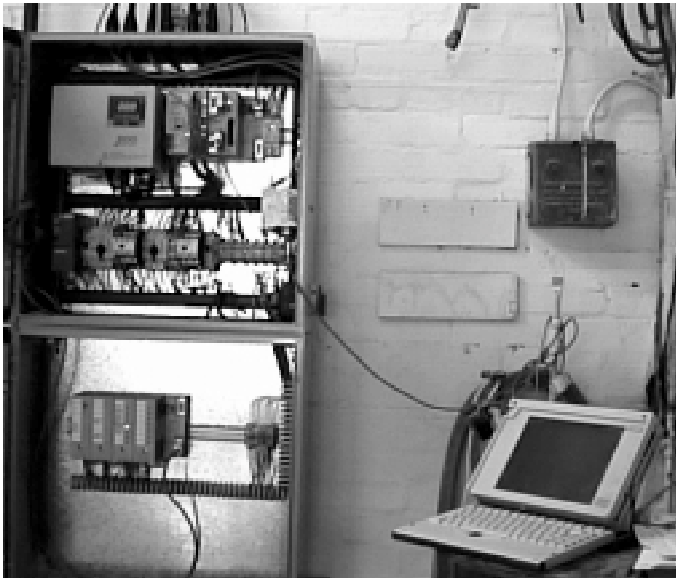


Figure 1.4 *A PLC system is housed in a cabinet, shown here with the door open. It controls the resin production plant illustrated in Fig. 1.2. The PLC controller is the small box mounted at the top left of the cabinet, with its control keys situated below its LED display. The low-voltage power supply is mounted to the right of the PLC. The input and output interface units are mounted on the rack below the PLC. Each may be connected to up to eight sensor or actuator devices. On the right is a laptop PC being used for writing programs and downloading them into the PLC. (By courtesy of Kronospan Ltd., Chirk)*

Controlling a chemical reaction

The use of PLCs in industry is illustrated by a stage in the manufacture of urea-formaldehyde resin (Fig. 1.2). There are several factors that determine whether the shutter should be opened or closed. For example, the shutter must be opened when the process begins, and must be closed when the kettle is full. Weighing sensors tell the CPU how much urea has been added to the kettle. Mixing urea with formaldehyde causes heat to be generated so a thermal sensor provides essential input to the CPU. The rate of addition of urea must be carefully controlled so that it does not overheat. The CPU controls another actuator which is a water valve which admits cold water to pipes surrounding the kettle. The program continually checks temperature and adjusts the rate of addition of urea and the rate of flow of cooling water accordingly.

continually reading input from the sensors, taking decisions and sending the appropriate output to the actuators. A typical program has a few hundred or thousand steps and take only a few tens of miliseconds to run, so the system responds reasonably quickly to changes in the state of the inputs.

The example of the valve demonstrates that it is not enough for the CPU to instruct actuators to move the shutter. There must also be sensors to check that the shutter is actually open or shut. This is to allow for the fact that it may not have had time to move to the required position. Or maybe it has jammed.

A system of the kind shown in Fig. 1.3 is common in industrial plant, whether it is a simple machine for filling cartridges with toner powder, a vast printing press, or a chemical plant producing insecticides. The main difference from one system to another is in the types and numbers of sensors and actuators attached to the system. The other main difference is the program that directs it. The program for the PLC is written by the operator, using special software running on a microcomputer. The PLC in Fig. 1.4 was in the process of being programmed by the laptop PC on the right. The program is tested on the microcomputer and, when it is free from bugs, downloaded into the memory of the PLC. Once the program is running correctly, the PC is disconnnected from the system and the PLC runs independently. The program is not normally altered except when there is to be a change in the operating procedure of the plant.

Bug: a programmer's term for an error in a program.

PCs and similar computers

There is much to be said about computer systems in later chapters, so for the present we will simply state the main ways in which they differ from the typical microcontroller systems described above. In essence, all computers have the same main features and we may take the typical personal computer (PC), as our example (Fig. 1.5).

The basic features are the same as in any microelectronic system: CPU, memory, input and output. Because the PC is intended to perform a wide range of often complex operations at high speed, a microprocessor is chosen as its CPU. Usually the system clock is a separate unit, as shown in Fig. 1.5. In contrast to systems such as the cordless telephone and PLCs, the PC has a full-sized keyboard, with over a hundred keys. It normally has a colour monitor.

The PC has several other input and output units either built into it or connected by special sockets. These include disk drives of various kinds, a mouse, and a printer. There may also be other devices such as

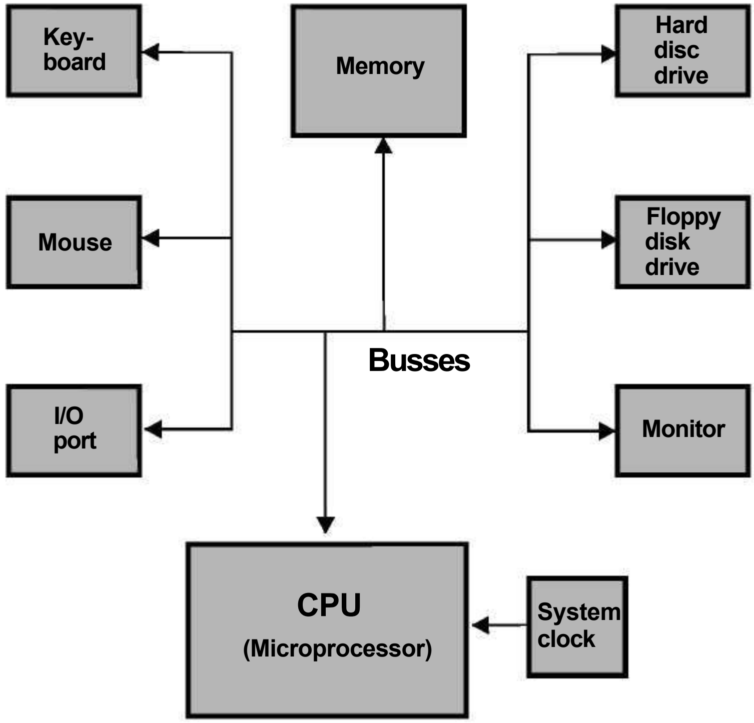


Figure 1.5 *This simplified diagram of a PC shows that it has much in common with the typical control systems of Figs. 1.1 and 1.3.*

Test your knowledge 1.5

What do we call the parallel set of conductors connecting the units in a microelectronic system?

a pair of loudspeakers, a joystick, a scanner and a digital camera.

One of the distinctive features of a PC and other computer-like systems is the *bus*. To assist the rapid transfer of data between the CPU and the other parts of the system the units are linked by a set of parallel conductors, shown for simplicity as a single conductor in Fig. 1.5. In practice, the bus consists of three separate busses, each with its own task, as will be explained in Chapter 2.

A PC is programmed from various sources. First of all, it has a block of permanent memory in which the operating system is stored. It has numerous programs stored on its disk drives, and the user can purchase other programs on compact discs, or download them from the Web. These programs are temporarily transferred to the computer's memory when they are to be run. Programs include word processors, spreadsheets, accounts programs, games, educational and training programs, and information programs such as dictionaries, encyclopaedias, telephone directories, catalogues and atlases. A wide range of specialised programs is obtainable for use by travel agents, theatre booking agents, medical centres, libraries and other medium sized organsations. Major businesses and organisations such as banks and oil companies employ software writers to produce programs intended for their operations (Fig. 1.6).

Figure 1.6 *Using a mouse to control a power station. The state-of-the-art control room at Ironbridge Power Station, Shropshire, uses computer monitors to display data readings taken at dozens of points in the steam-producing plant, in the turbines and in the electricity generators. The operator controls the power station by calling up a virtual control panel on the monitor. On this, the usual control switches, variable resistors, indicator lamps and meters are displayed in diagrammatic form. There is no keyboard on the computer. Instead, the operator uses a mouse to operate the controls, clicking on 'buttons' or dragging 'sliders' in just the same way as when playing a computer game. The station also has a basic conventional control panel with real switches for back-up in case of computer failure. (By courtesy of Eastern Generation Ltd.)*

Measuring instruments

Except in the cheapest models, the circuit of a digital multimeter (Fig. 1.7) centres on a microcontroller. This makes it possible for the multimeter to perform a range of functions quite beyond the scope of the conventional analogue multimeter, based on a moving-coil microammeter. The user of the digital meter simply selects what quantity is to be measured, applies the two probes to two test points in the circuit, and the reading automatically appears on the display. It is automatically updated several times per second. The display usually consists of 4 digits, with a movable decimal point and a polarity indicator (– for negative values). The quantities that can be measured include voltage, current, resistance, capacitance and frequency. With an ordinary multimeter the user has to select the range, but range selection is automatic with a meter based on a microcontroller.

Figure 1.7 *A multimeter is no longer a switched network of resistors and capacitors connected to a sensitive moving-coil microammeter. It still has the resistor and capacitor network, but now most of the switching is done by CMOS gates managed by a microcontroller.*

Given a constant current source, a timing circuit and a voltage-measuring circuit, it is possible to measure all the other quantities. Resistance can be measured by finding the voltage drop across the resistor when a given current flows through it. Capacitance can be measured by finding how long it takes a constant current to charge the capacitor to a given voltage. Frequency can be measured by timing the changes in voltage. These tests are easily automated for different ranges.

One of the few disadvantages of the numeric display of a digital meter is that, with a varying quantity, the rapidly changing figures do not help the user to visualise the way in which the value is changing. The needle of the conventional electromagnetic meter is much better for this purpose. The multimeter makes up for this with a bargraph display, which can be seen running along the lower margin of the display in Fig. 1.7.

The meter can also process the measurements. If the meter is run for a few minutes or more, the user can view the values as they change, or the microcontroller can be programmed to pick out the maximum value and the minimum value, and to calculate and display the difference between maximum and minimum, and the average value. It can also measure the voltage produced by a thermocouple and calculate the equivalent temperature in Celsius or Fahrenheit.

The next grade of microelectronic instruments above the multimeter is the *data logger.* In practice, these instruments perform two related but distinctive tasks:

- *Data acquisition* – receiving data (voltages, counts) from sensors.
- *Data logging* – recording data and processing it.

The Datataker (from Data Electronics), upon which this descripton is based, acquires measurements from a number of sensors connected to its array of input terminals. The measurements may be displayed on the Datataker's own screen or on the monitor of an attached computer. Subsequently the data can be stored (logged) in its own memory or on removable memory cards. The data can then be processed. For example, the device can calculate maxima, minima and other functions. It can also convert voltage, for example, into temperature in Celsius or Fahrenheit. The Datataker is able to perform its calculations at a higher level than the multimeter. For example, it has selectable routines for different types of thermocouple instead of being restricted to the one type supplied with the instrument. The scope of processing is increased by including statistical operations such as calculating standard deviations and plotting histograms. There are many other refinements in data presentation. For instance, each measurement is 'time and date stamped' with the time and date at which it was taken.

Another major bonus of the data logger is that it is programmable. It can be set to take periodic readings from a number of different sensors and store the results for display later. Or it may be set to produce an alarm output when values fall in a specified range. The data logger is programmed by using word-processing software running on a PC. It has its own specialised programming language. The finished program is downloaded from the PC into the Datataker. This can then run the program on its own, when it is no longer attached to the computer.

Distributed processing

In a conventional microelectronic system the CPU has direct control over all the input and output devices in the system. Figs. 1.1, 1.3 and 1.5 show examples of this. Now that a wide range of microcontrollers is available cheaply, a new approach to control has become more widespread. Each sensor or actuator in the system has its own microcontroller as an integral part of it. The microcontroller is programmed specifically to manage the action of the sensor or actuator. For example, consider an electric motor geared to an aileron in the wing of an aeroplane. When the aileron is to be moved, a command is sent from the central computer in the pilot's cockpit to the controller in the wing. The controller is then responsible for moving the aileron to its new angle. Normally it will accelerate it as fast as mechanical stresses allow until it reaches the maximum allowable rate of turning. This controlled acceleration involves complicated calculations by the microcontroller, based on previously determined parameters. There must be feedback of the actual position of the aileron to allow for mechanical effects such as wind resistance.

The controller has been told the angle at which the aileron is to finish so, *before* it reaches that position, the controller begins to decelerate it at the maximum allowable rate so that it finally comes to rest at exactly the required angle. While the action is in progress and when it is completed the processor reports back to the main computer. The main computer may also interrogate it at any stage to find out what angle the aileron has reached.

This is a reasonably complicated operation in which factors such as wind resistance must be taken into account. It is simpler for the task to be undertaken by an independent processor situated at the motor, than it is for all the ailerons and other control surfaces to be controlled from the central computer. In addition, this approach requires less cabling and is less subject to electromagnetic interference.

Distributed processing is part of the new 'fly by wire' principle adopted by Lucas Aerospace, as used in the A320 'Airbus' aeroplane.