MECHATRONICS

ELECTRONIC CONTROL SYSTEMS IN MECHANICAL AND ELECTRICAL ENGINEERING

WILLIAM BOLTON

SEVENTH EDITION

Pearson

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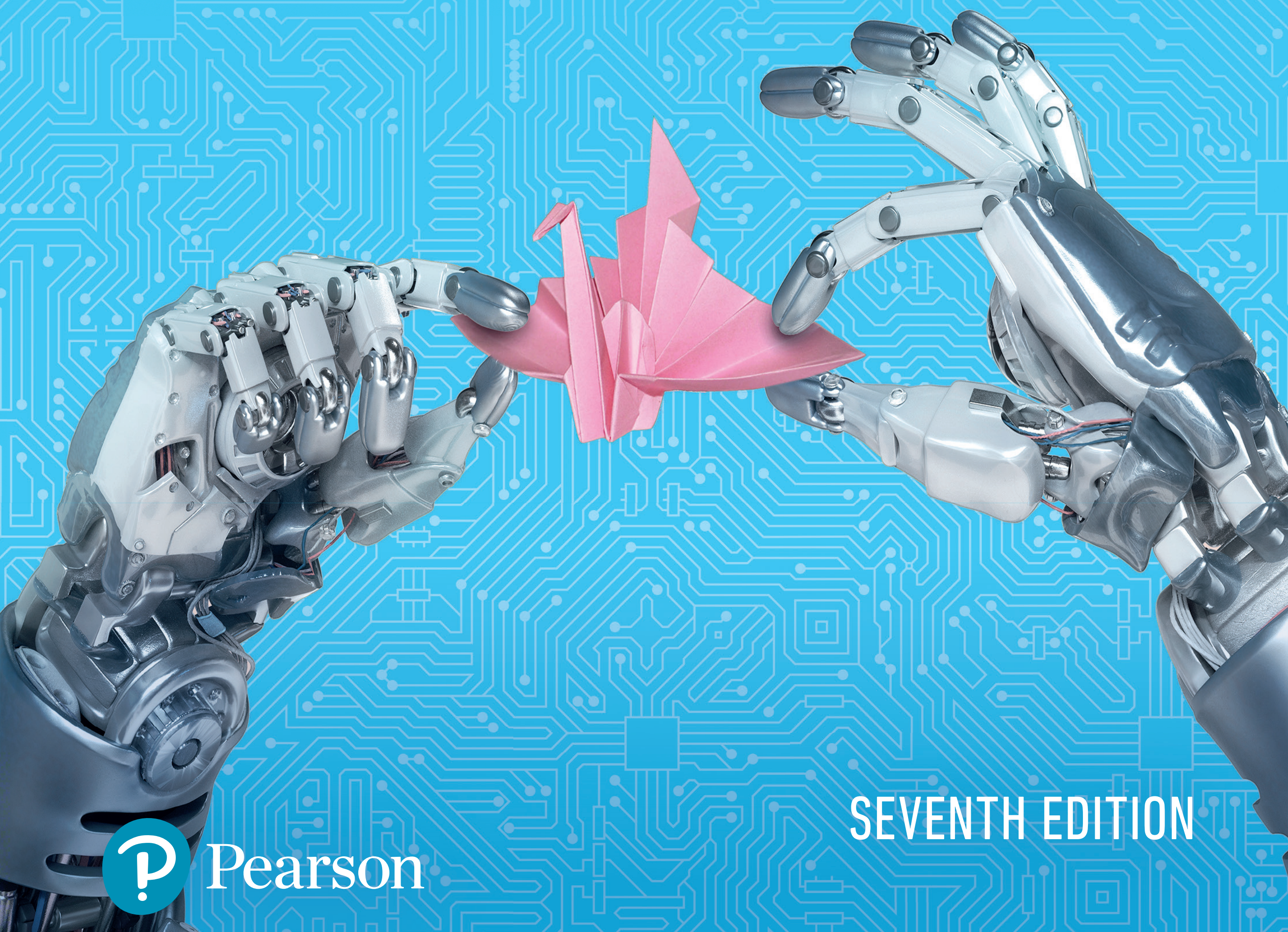

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William Bolton

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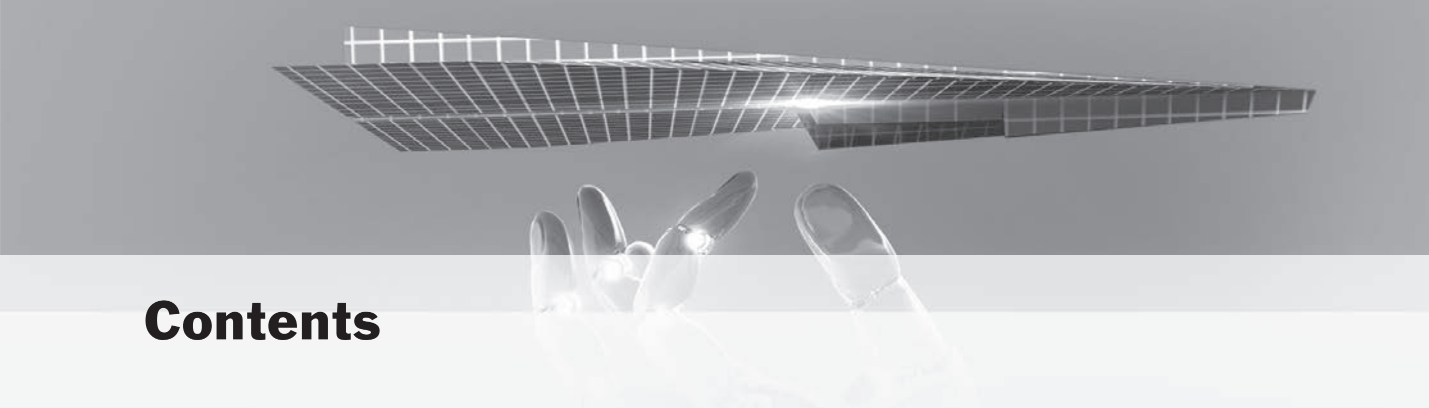

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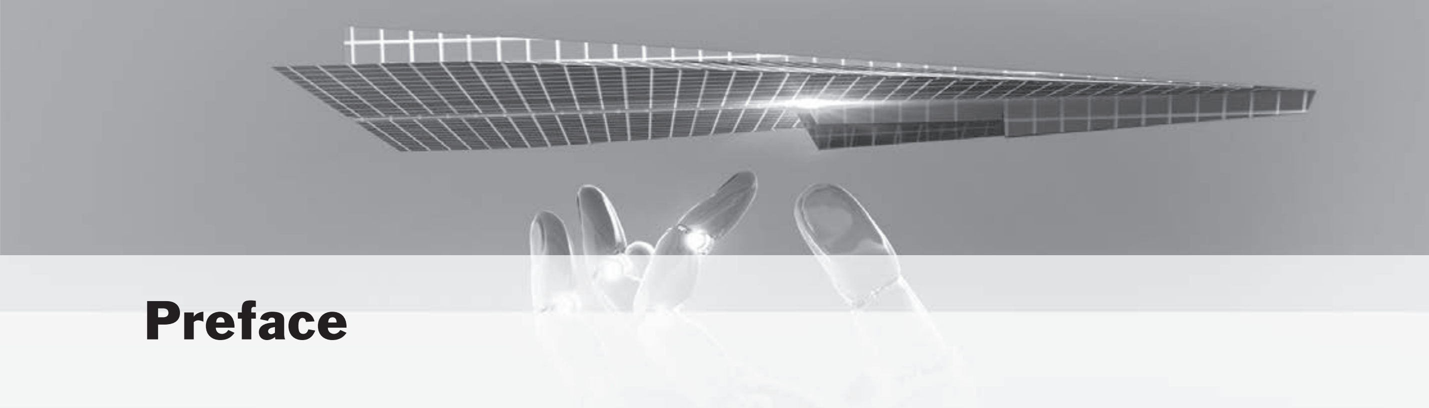


Preface

The term **mechatronics** was 'invented' by a Japanese engineer in 1969, as a combination of 'mecha' from mechanisms and 'tronics' from electronics. The word now has a wider meaning, being used to describe a philosophy in engineering technology in which there is a co-ordinated, and concurrently developed, integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes. As a result, many products which used to have mechanical functions have had many replaced with ones involving microprocessors. This has resulted in much greater flexibility, easier redesign and reprogramming, and the ability to carry out automated data collection and reporting.

A consequence of this approach is the need for engineers and technicians to adopt an interdisciplinary and integrated approach to engineering. Thus engineers and technicians need skills and knowledge that are not confined to a single subject area. They need to be capable of operating and communicating across a range of engineering disciplines and linking with those having more specialised skills. This book is an attempt to provide a basic background to mechatronics and provide links through to more specialised skills.

The first edition was designed to cover the Business and Technology Education Council (BTEC) Mechatronics units for Higher National Certificate/Diploma courses for technicians and designed to fit alongside more specialist units such as those for design, manufacture and maintenance determined by the application area of the course. The book was widely used for such courses and has also found use in undergraduate courses in both Britain and the United States. Following feedback from lecturers in both Britain and the United States, the second edition was considerably extended and with its extra depth it was not only still relevant for its original readership, but also suitable for undergraduate courses. The third edition involved refinements of some explanations, more discussion of microcontrollers and programming, increased use of models for mechatronic systems, and the grouping together of key facts in the Appendices. The fourth edition was a complete reconsideration of all aspects of the text, both layout and content, with some regrouping of topics, movement of more material into Appendices to avoid disrupting the flow of the text, new material – in particular an introduction to artificial intelligence – more case studies and a refinement of some topics to improve clarity. Also, objectives and key point summaries were included with each chapter. The fifth edition kept the same structure but, after consultation with many users of the book, many aspects had extra detail and refinement added.

The sixth edition involved a restructuring of the constituent parts of the book as some users felt that the chapter sequencing did not match the general teaching sequence. Other changes included the inclusion of material on

Arduino and the addition of more topics in the Mechatronic systems chapter. The seventh edition has continued the evolution of the book with updating of mechatronic system components, clarification of some aspects so they read more easily, the inclusion of information on the Atmega microcontrollers, a discussion and examples of fuzzy logic and neural control systems, and yet more applications and case studies. The number of Appendices has been reduced as they had grown over previous editions and it was felt that some were now little used. A revised and extended version of the Appendix concerning electrical circuit analysis has ben moved to the Instructor's Guide as Supporting material: Electrical components and circuits, and so is available to an instructor for issue to students if required.

The overall aim of the book is to give a comprehensive coverage of mechatronics which can be used with courses for both technicians and undergraduates in engineering and, hence, to help the reader:

- acquire a mix of skills in mechanical engineering, electronics and computing which is necessary if he/she is to be able to comprehend and design mechatronic systems;
- become capable of operating and communicating across the range of engineering disciplines necessary in mechatronics;
- be capable of designing mechatronic systems.

Each chapter of the book includes objectives and a summary, is copiously illustrated and contains problems, answers to which are supplied at the end of the book. Chapter 24 comprises research and design assignments together with clues as to their possible answers.

The structure of the book is as follows:

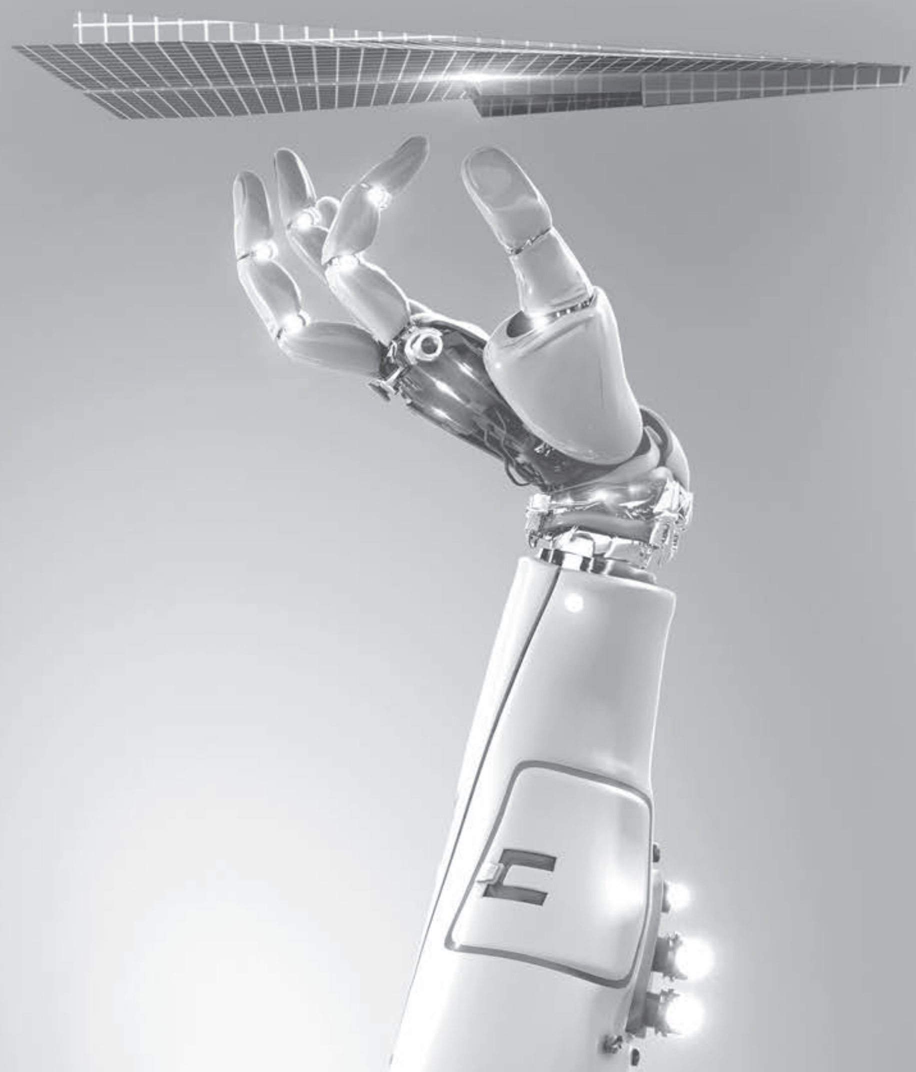
- Chapter 1 is a general introduction to mechatronics.
- Chapters 2–6 form a coherent block on sensors and signal conditioning.
- Chapters 7–9 cover actuators.
- Chapters 10–16 discuss microprocessor/microcontroller systems.
- Chapters 17–23 are concerned with system models.
- Chapter 24 provides an overall conclusion in considering the design of mechatronic systems.

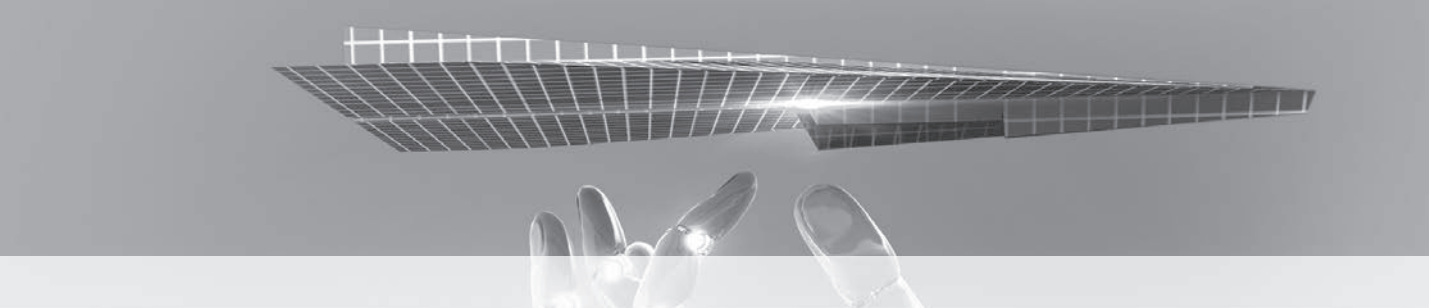
An Instructor's Guide, test material and PowerPoint slides are available for lecturers to download at: www.pearsoned.co.uk/bolton.

A large debt is owed to the publications of the manufacturers of the equipment referred to in the text. I would also like to thank those reviewers who painstakingly read through through the sixth edition and my proposals for this new edition and made suggestions for improvement.

W. Bolton

Part I
Introduction





Chapter one Introducing mechatronics

Objectives

The objectives of this chapter are that, after studying it, the reader should be able to:

- **Explain what is meant by mechatronics and appreciate its relevance in engineering design.**
- **Explain what is meant by a system and define the elements of measurement systems.**
- **Describe the various forms and elements of open-loop and closed-loop control systems.**
- **Recognise the need for models of systems in order to predict their behaviour.**

1.1 What is mechatronics?

The term **mechatronics** was 'invented' by a Japanese engineer in 1969, as a combination of 'mecha' from mechanisms and 'tronics' from electronics. The word now has a wider meaning, being used to describe a philosophy in engineering technology in which there is a co-ordinated, and concurrently developed, integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes. As a result, mechatronic products have many mechanical functions replaced with electronic ones. This results in much greater flexibility, easy redesign and reprogramming, and the ability to carry out automated data collection and reporting.

A mechatronic system is not just a marriage of electrical and mechanical systems and is more than just a control system; it is a complete integration of all of them in which there is a concurrent approach to the design. In the design of cars, robots, machine tools, washing machines, cameras and very many other machines, such an integrated and interdisciplinary approach to engineering design is increasingly being adopted. The integration across the traditional boundaries of mechanical engineering, electrical engineering, electronics and control engineering has to occur at the earliest stages of the design process if cheaper, more reliable, more flexible systems are to be developed. Mechatronics has to involve a concurrent approach to these disciplines rather than a sequential approach of developing, say, a mechanical system, then designing the electrical part and the microprocessor part. Thus mechatronics is a design philosophy, an integrating approach to engineering.

Mechatronics brings together areas of technology involving sensors and measurement systems, drive and actuation systems, and microprocessor systems (Figure 1.1), together with the analysis of the behaviour of systems and control systems. That essentially is a summary of this book. This chapter is an introduction to the topic, developing some of the basic concepts in order to give a framework for the rest of the book in which the details will be developed.

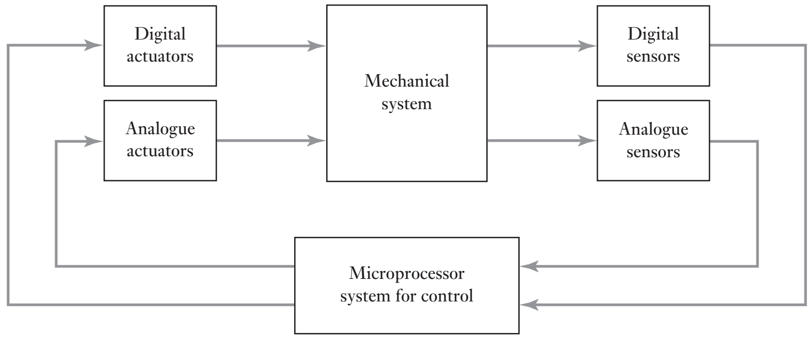


Figure 1.1 The basic elements of a mechatronic system.

1.1.1 Examples of mechatronic systems

Consider the modern autofocus, auto-exposure camera. To use the camera all you need to do is point it at the subject and press the button to take the picture. The camera can automatically adjust the focus so that the subject is in focus and automatically adjust the aperture and shutter speed so that the correct exposure is given. You do not have to manually adjust focusing and the aperture or shutter speed controls. Consider a truck's smart suspension. Such a suspension adjusts to uneven loading to maintain a level platform, adjusts to cornering, moving across rough ground, etc., to maintain a smooth ride. Consider an automated production line. Such a line may involve a number of production processes which are all automatically carried out in the correct sequence and in the correct way with a reporting of the outcomes at each stage in the process. The automatic camera, the truck suspension and the automatic production line are examples of a marriage between electronics, control systems and mechanical engineering.

1.1.2 Embedded systems

The term **embedded system** is used where microprocessors are embedded into systems and it is this type of system we are generally concerned with in mechatronics. A microprocessor may be considered as being essentially a collection of logic gates and memory elements that are not wired up as individual components but whose logical functions are implemented by means of software. As an illustration of what is meant by a logic gate, we might want an output if input *A* AND input *B* are both giving on signals. This could be implemented by what is termed an AND logic gate. An OR logic gate would give an output when either input *A* OR input *B* is on. A microprocessor is thus concerned with looking at inputs to see if they are on or off, processing the results of such an interrogation according to how it is programmed, and then giving outputs which are either on or off. See Chapter 10 for a more detailed discussion of microprocessors.

For a microprocessor to be used in a control system, it needs additional chips to give memory for data storage and for input/output ports to enable it to process signals from and to the outside world. **Microcontrollers** are microprocessors with these extra facilities all integrated together on a single chip.

An **embedded system** is a microprocessor-based system that is designed to control a range of functions and is not designed to be programmed by the end user in the same way that a computer is. Thus, with an embedded system, the user cannot change what the system does by adding or replacing software.

As an illustration of the use of microcontrollers in a control system, a modern washing machine will have a microprocessor-based control system to control the washing cycle, pumps, motor and water temperature. A modern car will have microprocessors controlling such functions as anti-lock brakes and engine management. Other examples of embedded systems are digital cameras, smart cards (credit-card-sized plastic cards embedded with a microprocessor able to store and process data), mobile phones (their SIM cards are just smart cards able to manage the rights of a subscriber on a network), printers, televisions, temperature controllers and indeed almost all the modern devices we have grown so accustomed to use to exercise control over situations.

1.2 The design process

The design process for any system can be considered as involving a number of stages.

1 *The need*
The design process begins with a need from, perhaps, a customer or client. This may be identified by market research being used to establish the needs of potential customers.

2 *Analysis of the problem*
The first stage in developing a design is to find out the true nature of the problem, i.e. analysing it. This is an important stage in that not defining the problem accurately can lead to wasted time on designs that will not fulfil the need.

3 *Preparation of a specification*
Following the analysis, a specification of the requirements can be prepared. This will state the problem, any constraints placed on the solution, and the criteria which may be used to judge the quality of the design. In stating the problem, all the functions required of the design, together with any desirable features, should be specified. Thus there might be a statement of mass, dimensions, types and range of motion required, accuracy, input and output requirements of elements, interfaces, power requirements, operating environment, relevant standards and codes of practice, etc.

4 *Generation of possible solutions*
This is often termed the **conceptual stage.** Outline solutions are prepared which are worked out in sufficient detail to indicate the means of obtaining each of the required functions, e.g. approximate sizes, shapes, materials and costs. It also means finding out what has been done before for similar problems; there is no sense in reinventing the wheel.

5 *Selections of a suitable solution*
The various solutions are evaluated and the most suitable one selected. Evaluation will often involve the representation of a system by a model and then simulation to establish how it might react to inputs.

6 *Production of a detailed design*
The detail of the selected design has now to be worked out. This might require the production of prototypes or mock-ups in order to determine the optimum details of a design.

7 *Production of working drawings*
The selected design is then translated into working drawings, circuit diagrams, etc., so that the item can be made.

It should not be considered that each stage of the design process just flows on stage by stage. There will often be the need to return to an earlier stage and give it further consideration. Thus, at the stage of generating possible solutions there might be a need to go back and reconsider the analysis of the problem.

1.2.1 Traditional and mechatronic designs

Engineering design is a complex process involving interactions between many skills and disciplines. With traditional design, the approach was for the mechanical engineer to design the mechanical elements, then the control engineer to come along and design the control system. This gives what might be termed a sequential approach to the design. However, the basis of the mechatronics approach is considered to lie in the concurrent inclusion of the disciplines of mechanical engineering, electronics, computer technology and control engineering in the approach to design. The inherent concurrency of this approach depends very much on system modelling and then simulation of how the model reacts to inputs and hence how the actual system might react to inputs.

As an illustration of how a multidisciplinary approach can aid in the solution of a problem, consider the design of bathroom scales. Such scales might be considered only in terms of the compression of springs and a mechanism used to convert the motion into rotation of a shaft and hence movement of a pointer across a scale; a problem that has to be taken into account in the design is that the weight indicated should not depend on the person's position on the scales. However, other possibilities can be considered if we look beyond a purely mechanical design. For example, the springs might be replaced by load cells with strain gauges and the output from them used with a microprocessor to provide a digital readout of the weight on an light-emitting diode (LED) display. The resulting scales might be mechanically simpler, involving fewer components and moving parts. The complexity has, however, been transferred to the software.

As a further illustration, the traditional design of the temperature control for a domestic central heating system has been the bimetallic thermostat in a closed-loop control system. The bending of the bimetallic strip changes as the temperature changes and is used to operate an on/off switch for the heating system. However, a multidisciplinary solution to the problem might be to use a microprocessor-controlled system employing perhaps a thermistor as the sensor. Such a system has many advantages over the bimetallic thermostat system. The bimetallic thermostat is comparatively crude and the temperature is not accurately controlled; also, devising a method for having different temperatures at different times of the day is complex and not easily achieved. The microprocessor-controlled system can, however, cope easily with giving precision and programmed control. The system is much more flexible. This improvement in flexibility is a common characteristic of mechatronic systems when compared with traditional systems.

1.3 Systems

In designing mechatronic systems, one of the steps involved is the creation of a model of the system so that predictions can be made regarding its behaviour when inputs occur. Such models involve drawing block diagrams to represent

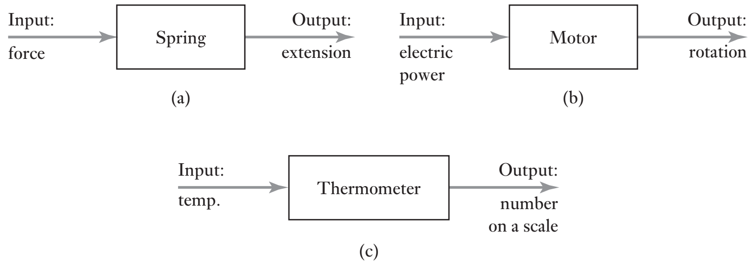


Figure 1.2 Examples of systems: (a) spring, (b) motor, (c) thermometer.

systems. A **system** can be thought of as a box or block diagram which has an input and an output and where we are concerned not with what goes on inside the box, but with only the relationship between the output and the input. The term **modelling** is used when we represent the behaviour of a real system by mathematical equations, such equations representing the relationship between the inputs and outputs from the system. For example, a spring can be considered as a system to have an input of a force F and an output of an extension x (Figure 1.2(a)). The equation used to model the relationship between the input and output might be $F = kx$, where k is a constant. As another example, a motor may be thought of as a system which has as its input electric power and as output the rotation of a shaft (Figure 1.2(b)).

A **measurement system** can be thought of as a box which is used for making measurements. It has as its input the quantity being measured and its output the value of that quantity. For example, a temperature measurement system, i.e. a thermometer, has an input of temperature and an output of a number on a scale (Figure 1.2(c)).

1.3.1 Modelling systems

The response of any system to an input is not instantaneous. For example, for the spring system described by Figure 1.2(a), though the relationship between the input, force F, and output, extension x, was given as $F = kx$, this only describes the relationship when steady-state conditions occur. When the force is applied it is likely that oscillations will occur before the spring settles down to its steady-state extension value (Figure 1.3). The responses of systems are functions of time. Thus, in order to know how systems behave when there are inputs to them, we need to devise models for systems which relate the output to the input so that we can work out, for a given input, how the output will vary with time and what it will settle down to.

As another example, if you switch on a kettle it takes some time for the water in the kettle to reach boiling point (Figure 1.4). Likewise, when a

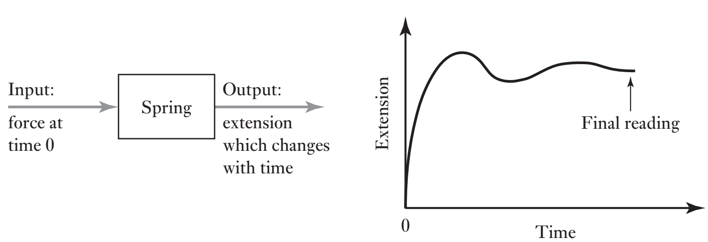


Figure 1.3 The response to an input for a spring.

Figure 1.4 The response to an input for a kettle system.

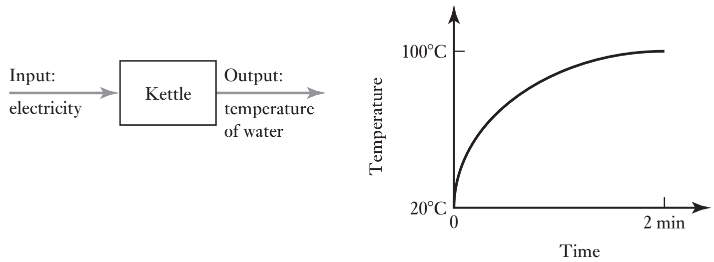
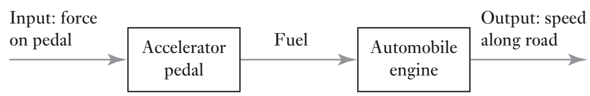


Figure 1.5 An automobile driving system.



microprocessor controller gives a signal to, say, move the lens for focusing in an automatic camera, then it takes time before the lens reaches its position for correct focusing.

Often the relationship between the input and output for a system is described by a differential equation. Such equations and systems are discussed in Chapter 17.

1.3.2 Connected systems

In other than the simplest system, it is generally useful to consider the system as a series of interconnected blocks, each such block having a specific function. We then have the output from one block becoming the input to the next block in the system. In drawing a system in this way, it is necessary to recognise that lines drawn to connect boxes indicate a flow of information in the direction indicated by an arrow and not necessarily physical connections. An example of such a connected system is the driving system of an automobile. We can think of there being two interconnected blocks: the accelerator pedal which has an input of force applied by a foot to the accelerator pedal system and controls an output of fuel, and the engine system which has an input of fuel and controls an output of speed along a road (Figure 1.5). Another example of such a set of connected blocks is given in the next section on measurement systems.

1.4 Measurement systems

Of particular importance in any discussion of mechatronics are measurement systems. **Measurement systems** can, in general, be considered to be made up of three basic elements (as illustrated in Figure 1.6):

1 A **sensor** responds to the quantity being measured by giving as its output a signal which is related to the quantity. For example, a thermocouple is a temperature sensor. The input to the sensor is a temperature and the output is an e.m.f., which is related to the temperature value.

2 A **signal conditioner** takes the signal from the sensor and manipulates it into a condition which is suitable either for display or, in the case of a control system, for use to exercise control. Thus, for example, the output from a

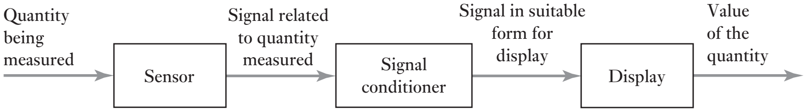


Figure 1.6 A measurement system and its constituent elements.

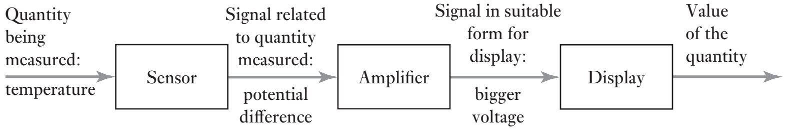


Figure 1.7 A digital thermometer system.

thermocouple is a rather small e.m.f. and might be fed through an amplifier to obtain a bigger signal. The amplifier is the signal conditioner.

3 A **display system** displays the output from the signal conditioner. This might, for example, be a pointer moving across a scale or a digital readout.

As an example, consider a digital thermometer (Figure 1.7). This has an input of temperature to a sensor, probably a semiconductor diode. The potential difference across the sensor is, at constant current, a measure of the temperature. This potential difference is then amplified by an operational amplifier to give a voltage which can directly drive a display. The sensor and operational amplifier may be incorporated on the same silicon chip.

Sensors are discussed in Chapter 2 and signal conditioners in Chapter 3. Measurement systems involving all elements are discussed in Chapter 6.

1.5 Control systems

A **control system** can be thought of as a system which can be used to:

1 control some variable to some particular value, e.g. a central heating system where the temperature is controlled to a particular value;
2 control the sequence of events, e.g. a washing machine where when the dials are set to, say, 'white' and the machine is then controlled to a particular washing cycle, i.e. sequence of events, appropriate to that type of clothing;
3 control whether an event occurs or not, e.g. a safety lock on a machine where it cannot be operated until a guard is in position.

1.5.1 Feedback

Consider an example of a control system with which we are all individually involved. Your body temperature, unless you are ill, remains almost constant regardless of whether you are in a cold or hot environment. To maintain this constancy your body has a temperature control system. If your temperature begins to increase above the normal you sweat; if it decreases you shiver. Both these are mechanisms which are used to restore the body temperature back to its normal value. The control system is maintaining constancy of temperature. The system has an input from sensors which tell it what the temperature is and then compare this data with what the temperature should be and provide the appropriate response in order to obtain the required temperature. This is an example of **feedback control**: signals are fed back from the output, i.e. the actual