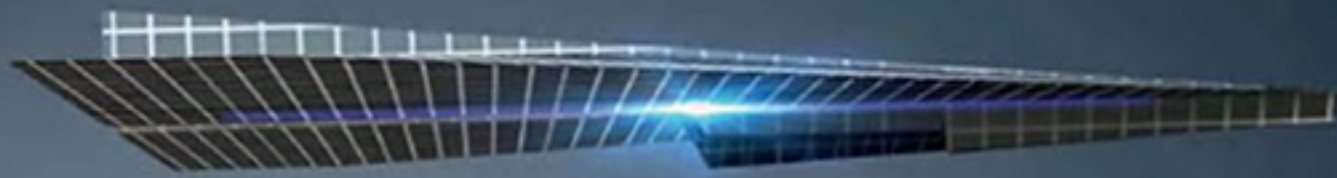


# MECHATRONICS

ELECTRONIC CONTROL SYSTEMS IN  
MECHANICAL AND ELECTRICAL ENGINEERING

SIXTH EDITION



WILLIAM BOLTON

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ELECTRONIC CONTROL SYSTEMS  
IN MECHANICAL AND ELECTRICAL  
ENGINEERING

Sixth Edition

William Bolton

PEARSON

First published 1995 (print)  
Second edition published 1999 (print)  
Third edition published 2003 (print)  
Fourth edition published 2008 (print)  
Fifth edition published 2011 (print and electronic)  
**Sixth edition published 2015 (print and electronic)**

© Pearson Education Limited 2015 (print and electronic)

ISBN: 978-1-292-07668-3 (print)  
978-1-292-08159-5 (PDF)  
978-1-292-08160-1 (eText)

**British Library Cataloguing-in-Publication Data**

A catalogue record for the print edition is available from the British Library

**Library of Congress Cataloguing-in-Publication Data**

Bolton, W. (William), 1933–

Mechatronics : a multidisciplinary approach / William Bolton. – Sixth edition.

pages cm

Includes bibliographical references and index.

ISBN 978-1-292-07668-3

1. Mechatronics. I. Title.

TJ163.12.B65 2015

621–dc23

2014041487

# Contents

Preface	xi		
<b>I. Introduction</b>	<b>1</b>	<b>3. Signal conditioning</b>	<b>69</b>
<b>1. Introducing mechatronics</b>	<b>3</b>	Chapter objectives	69
Chapter objectives	3	3.1 Signal conditioning	69
1.1 What is mechatronics?	3	3.2 The operational amplifier	70
1.2 The design process	5	3.3 Protection	81
1.3 Systems	6	3.4 Filtering	83
1.4 Measurement systems	8	3.5 Wheatstone bridge	84
1.5 Control systems	9	3.6 Pulse modulation	88
1.6 Programmable logic controller	21	3.7 Problems with signals	89
1.7 Examples of mechatronic systems	22	3.8 Power transfer	92
Summary	25	Summary	92
Problems	26	Problems	93
<b>II. Sensors and signal conditioning</b>	<b>27</b>	<b>4. Digital signals</b>	<b>95</b>
<b>2. Sensors and transducers</b>	<b>29</b>	Chapter objectives	95
Chapter objectives	29	4.1 Digital signals	95
2.1 Sensors and transducers	29	4.2 Analogue and digital signals	95
2.2 Performance terminology	30	4.3 Digital-to-analogue and analogue-to-digital converters	99
2.3 Displacement, position and proximity	35	4.4 Multiplexers	105
2.4 Velocity and motion	46	4.5 Data acquisition	106
2.5 Force	49	4.6 Digital signal processing	109
2.6 Fluid pressure	50	Summary	110
2.7 Liquid flow	54	Problems	110
2.8 Liquid level	55	<b>5. Digital logic</b>	<b>112</b>
2.9 Temperature	56	Chapter objectives	112
2.10 Light sensors	61	5.1 Digital logic	112
2.11 Selection of sensors	62	5.2 Logic gates	113
2.12 Inputting data by switches	63	5.3 Applications of logic gates	120
Summary	65	5.4 Sequential logic	126
Problems	66	Summary	133
		Problems	133

**6. Data presentation systems 136**

Chapter objectives	136
6.1 Displays	136
6.2 Data presentation elements	137
6.3 Magnetic recording	142
6.4 Optical recording	146
6.5 Displays	147
6.6 Data acquisition systems	151
6.7 Measurement systems	155
6.8 Testing and calibration	158
Summary	160
Problems	160

**III. Actuation 163****7. Pneumatic and hydraulic actuation systems 165**

Chapter objectives	165
7.1 Actuation systems	165
7.2 Pneumatic and hydraulic systems	165
7.3 Directional control valves	169
7.4 Pressure control valves	173
7.5 Cylinders	175
7.6 Servo and proportional control valves	178
7.7 Process control valves	180
7.8 Rotary actuators	185
Summary	186
Problems	186

**8. Mechanical actuation systems 188**

Chapter objectives	188
8.1 Mechanical systems	188
8.2 Types of motion	189
8.3 Kinematic chains	191
8.4 Cams	194
8.5 Gears	196
8.6 Ratchet and pawl	200
8.7 Belt and chain drives	200
8.8 Bearings	202
Summary	204
Problems	205

**9. Electrical actuation systems 207**

Chapter objectives	207
9.1 Electrical systems	207
9.2 Mechanical switches	207
9.3 Solid-state switches	209
9.4 Solenoids	215
9.5 Direct current motors	217
9.6 Alternating current motors	225
9.7 Stepper motors	227
9.8 Motor selection	234
Summary	237
Problems	237

**IV. Microprocessor systems 239****10. Microprocessors and microcontrollers 241**

Chapter objectives	241
10.1 Control	241
10.2 Microprocessor systems	241
10.3 Microcontrollers	253
10.4 Applications	272
10.5 Programming	274
Summary	277
Problems	277

**11. Assembly language 278**

Chapter objective	278
11.1 Languages	278
11.2 Instruction sets	279
11.3 Assembly language programs	285
11.4 Subroutines	290
11.5 Look-up tables	293
11.6 Embedded systems	296
Summary	300
Problems	300

**12. C language 302**

Chapter objectives	302
12.1 Why C?	302
12.2 Program structure	302

12.3	Branches and loops	309	15.3	Networks	379
12.4	Arrays	313	15.4	Protocols	381
12.5	Pointers	315	15.5	Open Systems Interconnection communication model	382
12.6	Program development	316	15.6	Serial communication interfaces	385
12.7	Examples of programs	317	15.7	Parallel communication interfaces	391
12.8	Arduino programs	320	15.8	Wireless protocols	394
	Summary	323		Summary	395
	Problems	324		Problems	395

### **13. Input/output systems 326**

	Chapter objectives	326
13.1	Interfacing	326
13.2	Input/output addressing	326
13.3	Interface requirements	329
13.4	Peripheral interface adapters	336
13.5	Serial communications interface	341
13.6	Examples of interfacing	344
	Summary	347
	Problems	348

### **14. Programmable logic controllers 349**

	Chapter objectives	349
14.1	Programmable logic controller	349
14.2	Basic PLC structure	349
14.3	Input/output processing	353
14.4	Ladder programming	354
14.5	Instruction lists	358
14.6	Latching and internal relays	361
14.7	Sequencing	363
14.8	Timers and counters	364
14.9	Shift registers	367
14.10	Master and jump controls	368
14.11	Data handling	369
14.12	Analogue input/output	371
	Summary	373
	Problems	374

### **15. Communication systems 376**

	Chapter objectives	376
15.1	Digital communications	376
15.2	Centralised, hierarchical and distributed control	376

### **16. Fault finding 397**

	Chapter objectives	397
16.1	Fault-detection techniques	397
16.2	Watchdog timer	398
16.3	Parity and error coding checks	399
16.4	Common hardware faults	400
16.5	Microprocessor systems	402
16.6	Emulation and simulation	405
16.7	PLC systems	407
	Summary	409
	Problems	410

### **V. System models 411**

#### **17. Basic system models 413**

	Chapter objectives	413
17.1	Mathematical models	413
17.2	Mechanical system building blocks	414
17.3	Electrical system building blocks	422
17.4	Fluid system building blocks	426
17.5	Thermal system building blocks	433
	Summary	436
	Problems	437

#### **18. System models 439**

	Chapter objectives	439
18.1	Engineering systems	439
18.2	Rotational–translational systems	439
18.3	Electro–mechanical systems	440
18.4	Linearity	443
18.5	Hydraulic–mechanical systems	445
	Summary	448
	Problems	448

<b>19. Dynamic responses of systems</b>	<b>449</b>		
Chapter objectives	449		
19.1 Modelling dynamic systems	449	22.4 Proportional mode	510
19.2 Terminology	450	22.5 Derivative control	512
19.3 First-order systems	452	22.6 Integral control	514
19.4 Second-order systems	458	22.7 PID controller	516
19.5 Performance measures for second-order systems	464	22.8 Digital controllers	517
19.6 System identification	467	22.9 Control system performance	520
Summary	467	22.10 Controller tuning	521
Problems	469	22.11 Velocity control	523
		22.12 Adaptive control	523
		Summary	526
		Problems	527
<b>20. System transfer functions</b>	<b>471</b>		
Chapter objectives	471		
20.1 The transfer function	471	<b>23. Artificial intelligence</b>	<b>528</b>
20.2 First-order systems	474	Chapter objectives	528
20.3 Second-order systems	476	23.1 What is meant by artificial intelligence?	528
20.4 Systems in series	478	23.2 Perception and cognition	528
20.5 Systems with feedback loops	479	23.3 Reasoning	530
20.6 Effect of pole location on transient response	480	23.4 Learning	533
Summary	484	Summary	534
Problems	484	Problems	534
		<b>VI. Conclusion</b>	<b>535</b>
<b>21. Frequency response</b>	<b>486</b>		
Chapter objectives	486	<b>24. Mechatronic systems</b>	<b>537</b>
21.1 Sinusoidal input	486	Chapter objectives	537
21.2 Phasors	487	24.1 Mechatronic designs	537
21.3 Frequency response	489	24.2 Case studies	548
21.4 Bode plots	492	24.3 Robotics	563
21.5 Performance specifications	501	Summary	567
21.6 Stability	502	Problems	567
Summary	503	Research assignments	568
Problems	504	Design assignments	568
		<b>Appendices</b>	<b>569</b>
<b>22. Closed-loop controllers</b>	<b>505</b>	<b>A The Laplace transform</b>	<b>571</b>
Chapter objectives	505	A.1 The Laplace transform	571
22.1 Continuous and discrete control processes	505	A.2 Unit steps and impulses	572
22.2 Terminology	507	A.3 Standard Laplace transforms	574
22.3 Two-step mode	509	A.4 The inverse transform	578
		Problems	580

<b>B</b>	<b>Number systems</b>	<b>581</b>	<b>E</b>	<b>C library functions</b>	<b>601</b>
B.1	Number systems	581			
B.2	Binary mathematics	582			
B.3	Floating numbers	585			
B.4	Gray code	585			
	Problems	586			
<b>C</b>	<b>Boolean algebra</b>	<b>587</b>	<b>F</b>	<b>MATLAB and SIMULINK</b>	<b>604</b>
C.1	Laws of Boolean algebra	587	F.1	MATLAB	604
C.2	De Morgan's laws	588	F.2	SIMULINK	608
C.3	Boolean function generation from truth tables	589			
C.4	Karnaugh maps	591			
	Problems	594			
<b>D</b>	<b>Instruction sets</b>	<b>596</b>	<b>G</b>	<b>Electrical circuit analysis</b>	<b>610</b>
			G.1	Direct current circuits	610
			G.2	Alternating current circuits	615
				Further information	620
				Answers	624
				Index	639



# 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 in 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 mechatronics 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 has 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. Thus the new edition has involved moving the system models part so that it comes after microprocessor systems. Other changes include the inclusion of material on Arduino and the addition of more topics in the Mechatronics Systems chapter.

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 mechatronics 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:

- 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](http://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 the fifth edition and made suggestions for improvements.

W. Bolton

# 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

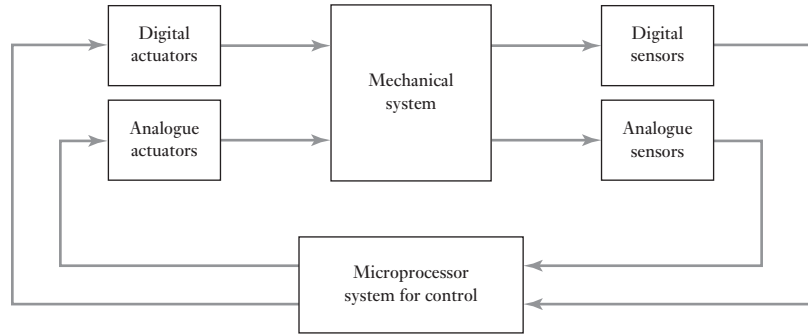
### What is mechatronics?

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 aperture or shutter speed controls. Consider a truck 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 autofocus, auto-exposure cameras, camcorders, cell phones, DVD players, electronic card readers, photocopiers, printers, scanners, televisions and temperature controllers.

## 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 when 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 mechatronics 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 thermodiode 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 mechatronics systems when compared with traditional systems.

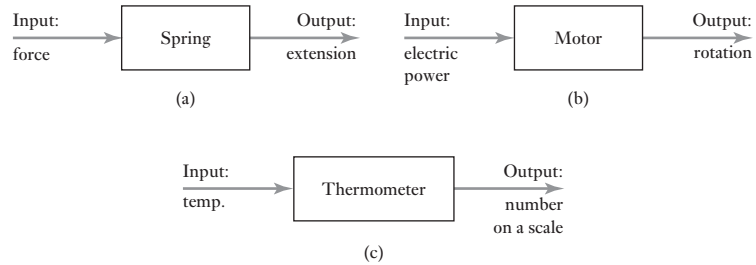
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## 1.3

### 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 systems. A **system** can be thought of as a box or block diagram

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



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)).

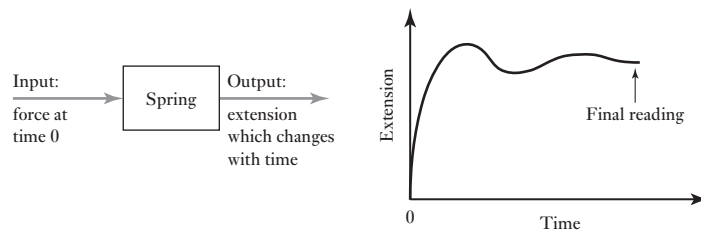
A **measurement system** can be thought of as a box which is used for making measurements. It has as its input the quantity being measured and its output the value of that quantity. For example, a temperature measurement system, i.e. a thermometer, has an input of temperature and an output of a number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

### 1.3.1 Modelling systems

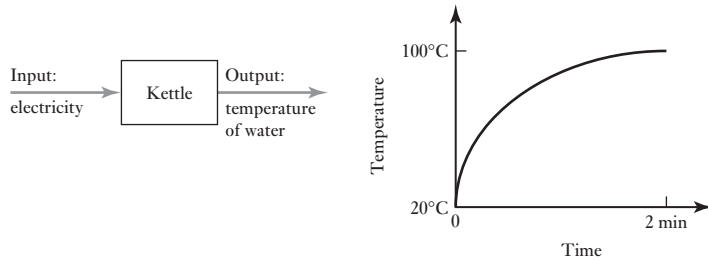
The response of any system to an input is not instantaneous. For example, for the spring system described by Figure 1.2(a), though the relationship between the input, force  $F$ , and output, extension  $x$ , was given as  $F = kx$ , this only describes the relationship when steady-state conditions occur. 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 microprocessor controller gives a signal to, say, move the lens for focusing

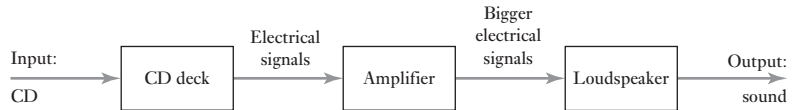
**Figure 1.3** The response to an input for a spring.



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



**Figure 1.5** A CD player.



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 it 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 a CD player. We can think of there being three interconnected blocks: the CD deck which has an input of a CD and an output of electrical signals; an amplifier which has an input of these electrical signals, and an output of bigger electrical signals; and a speaker which has an input of the electrical signals and an output of sound (Figure 1.5). Another example of such a set of connected blocks is given in the next section on measurement systems.

## 1.4

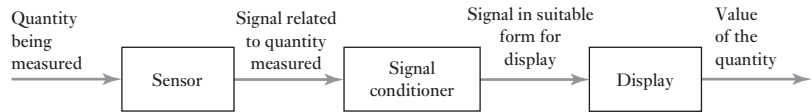
### Measurement systems

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).

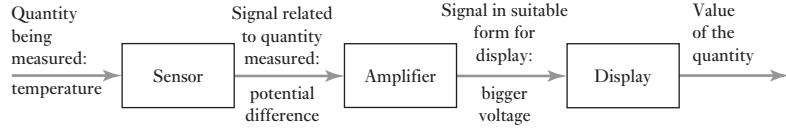
- 1 A **sensor** responds to the quantity being measured by giving as its output a signal which is related to the quantity. For example, a thermocouple is a temperature sensor. The input to the sensor is a temperature and the output is an e.m.f., which is related to the temperature value.
- 2 A **signal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



**Figure 1.6** A measurement system and its constituent elements.



**Figure 1.7** A digital thermometer system.



from a 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

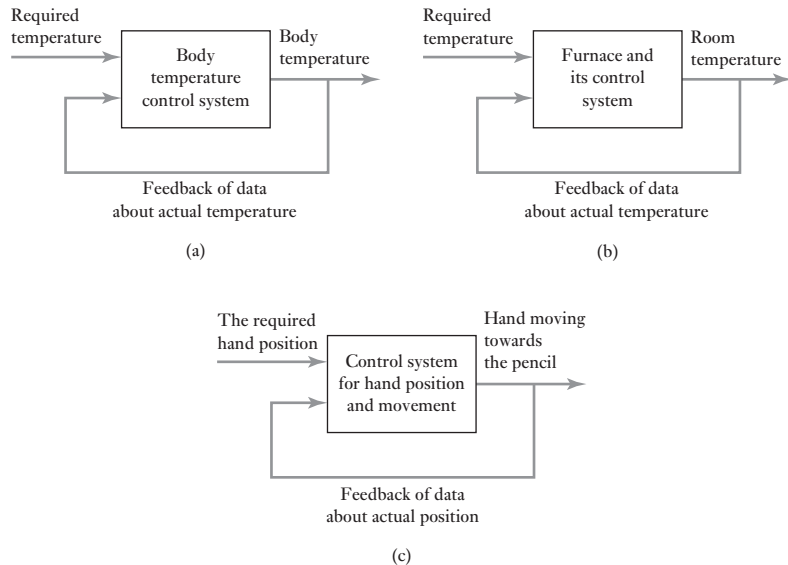
A **control system** can be thought of as a system which can be used to:

- 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

**Figure 1.8** Feedback control: (a) human body temperature, (b) room temperature with central heating, (c) picking up a pencil.



temperature. This is an example of **feedback control**: signals are fed back from the output, i.e. the actual temperature, in order to modify the reaction of the body to enable it to restore the temperature to the ‘normal’ value. Feedback control is exercised by the control system comparing the fed-back actual output of the system with what is required and adjusting its output accordingly. Figure 1.8(a) illustrates this feedback control system.

One way to control the temperature of a centrally heated house is for a human to stand near the furnace on/off switch with a thermometer and switch the furnace on or off according to the thermometer reading. That is a crude form of feedback control using a human as a control element. The term feedback is used because signals are fed back from the output in order to modify the input. The more usual feedback control system has a thermostat or controller which automatically switches the furnace on or off according to the difference between the set temperature and the actual temperature (Figure 1.8(b)). This control system is maintaining constancy of temperature.

If you go to pick up a pencil from a bench there is a need for you to use a control system to ensure that your hand actually ends up at the pencil. This is done by your observing the position of your hand relative to the pencil and making adjustments in its position as it moves towards the pencil. There is a feedback of information about your actual hand position so that you can modify your reactions to give the required hand position and movement (Figure 1.8(c)). This control system is controlling the positioning and movement of your hand.

Feedback control systems are widespread, not only in nature and the home but also in industry. There are many industrial processes and machines where control, whether by humans or automatically, is required. For example, there is process control where such things as temperature, liquid level, fluid flow, pressure, etc., are maintained constant. Thus in a chemical process there may be a need to maintain the level of a liquid in a tank to a particular level or to a particular temperature. There are also control systems which involve consistently and accurately positioning a moving part or maintaining a constant speed. This might be, for example, a motor designed to run

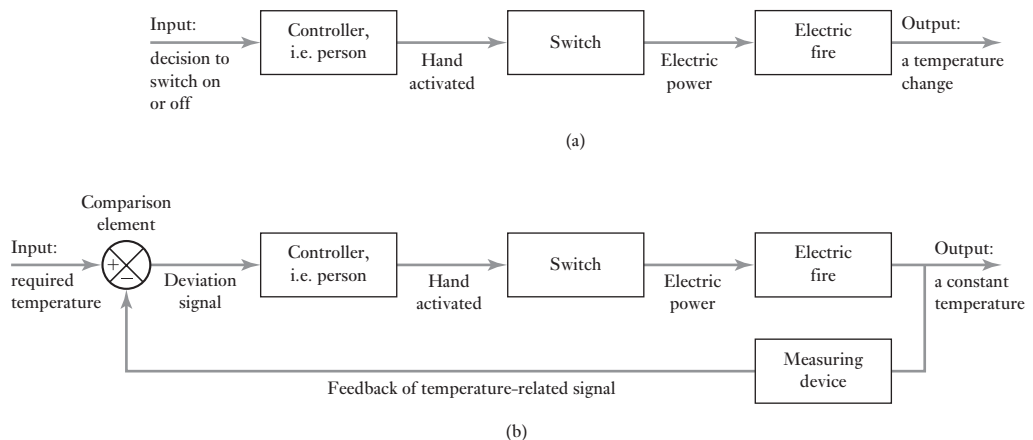
at a constant speed or perhaps a machining operation in which the position, speed and operation of a tool are automatically controlled.

### 1.5.2 Open- and closed-loop systems

There are two basic forms of control system, one being called **open loop** and the other **closed loop**. The difference between these can be illustrated by a simple example. Consider an electric fire which has a selection switch which allows a 1 kW or a 2 kW heating element to be selected. If a person used the heating element to heat a room, he or she might just switch on the 1 kW element if the room is not required to be at too high a temperature. The room will heat up and reach a temperature which is only determined by the fact that the 1 kW element was switched on and not the 2 kW element. If there are changes in the conditions, perhaps someone opening a window, there is no way the heat output is adjusted to compensate. This is an example of open-loop control in that there is no information fed back to the element to adjust it and maintain a constant temperature. The heating system with the heating element could be made a closed-loop system if the person has a thermometer and switches the 1 kW and 2 kW elements on or off, according to the difference between the actual temperature and the required temperature, to maintain the temperature of the room constant. In this situation there is feedback, the input to the system being adjusted according to whether its output is the required temperature. This means that the input to the switch depends on the deviation of the actual temperature from the required temperature, the difference between them being determined by a comparison element – the person in this case. Figure 1.9 illustrates these two types of system.

An example of an everyday open-loop control system is the domestic toaster. Control is exercised by setting a timer which determines the length of time for which the bread is toasted. The brownness of the resulting toast is determined solely by this preset time. There is no feedback to control the degree of browning to a required brownness.

To illustrate further the differences between open- and closed-loop systems, consider a motor. With an open-loop system the speed of rotation of the shaft might be determined solely by the initial setting of a knob which



**Figure 1.9** Heating a room: (a) an open-loop system, (b) a closed-loop system.