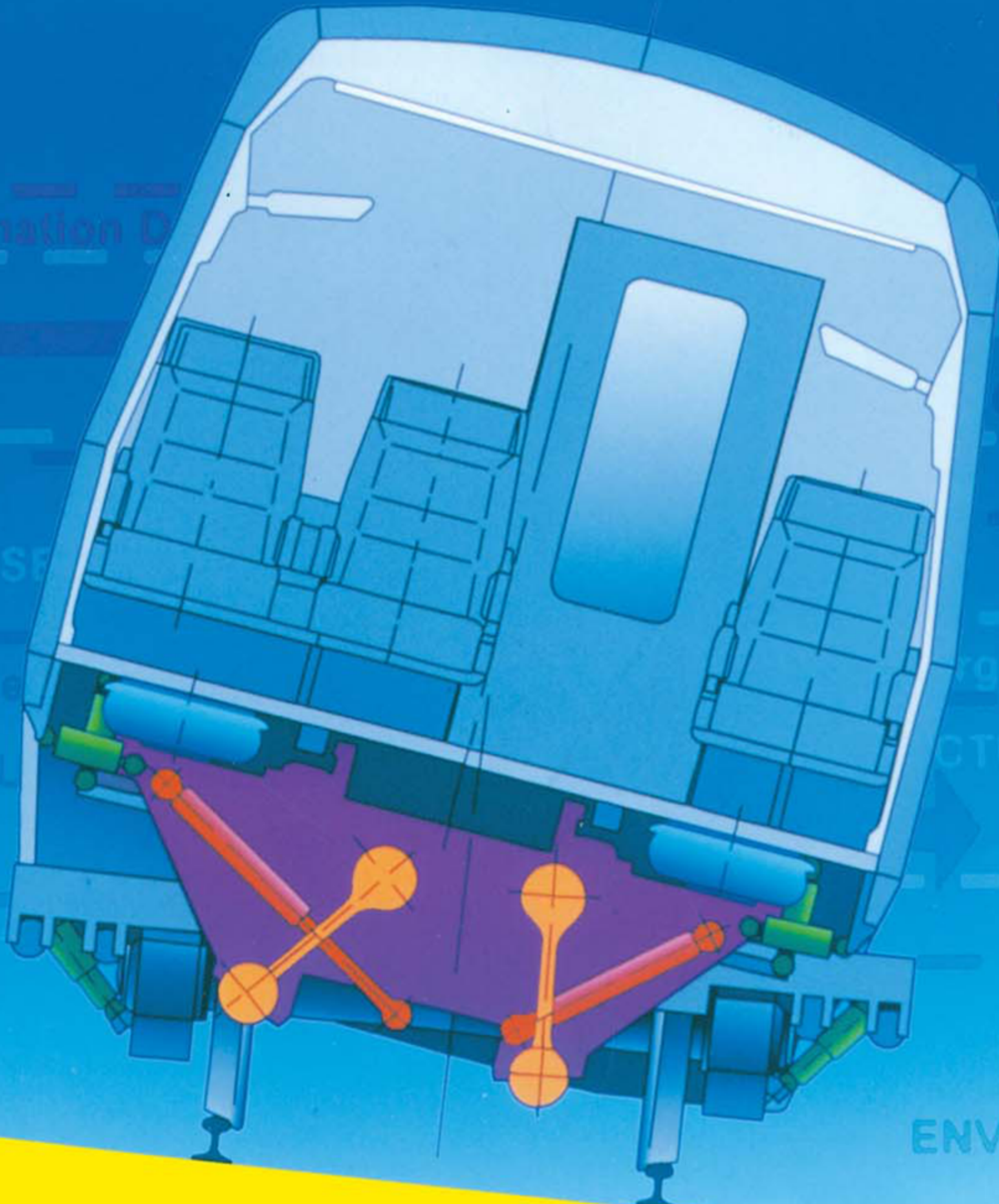
Mechatronics

and the design of intelligent machines and systems



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Preface

The past few years have seen mechatronics have an increasing impact on engineering and engineering education as a defining approach to the design, development and operation of an increasingly wide range of engineering systems. In addition, mechatronics is now recognised as involving not only the technical aspects of its core disciplines – mechanical engineering, electrical and electronic engineering and software – but also aspects of organisation, training and management. Indeed, in its approach to engineering product development, mechatronics has much in common with concurrent engineering strategies.

The WHAT of mechatronics
It can be argued that it is the development of the microprocessor and the subsequent growth in microelectronics technologies and the support that it provides for the 'transfer of complexity' from the mechanical to the electronic and software domains that is at the heart of mechatronics. The resulting systems are more complex with higher levels of performance and greater reliability than their predecessors, all achieved at significantly reduced real costs.

The WHY of mechatronics
In an increasingly competitive and global market, companies need to have the ability to increase the competitiveness of their products through the use of technology and must be able to respond rapidly and effectively to changes in the market place. Mechatronic strategies have been shown to support and enable the development of new products and markets such as the compact disc player as well as through enhancing existing products while responding to the introduction of new product lines by a competitor.

The influence of mechatronics as a driver of the product development process is perhaps most strongly witnessed in the automotive industry where vehicle systems have become increasingly more mechatronic in nature with features such as engine management systems, traction control and ABS now commonplace. Future developments include drive-by-wire, collision avoidance systems, lane tracking and navigational control.

However, and whatever the level of technology, the motivation for the adoption by a company of a mechatronic approach to product development and manufacturing must be one of providing the company with a strategic and commercial advantage either through the development of new and novel products, through the enhancement of existing products, by gaining access to new markets or some combination of these factors.

The HOW of mechatronics

The achievement of a successful mechatronics design environment essentially depends on the ability of the design team to communicate, collaborate and integrate. Indeed, a major role of the mechatronics engineer is often that of acting to bridge the communications gaps that can exist between more specialist colleagues in order to ensure that the objectives of collaboration and integration are achieved. This is important during the design phases of product development and particularly so in relation to requirements definition where errors in interpretation of customer requirements can result in significant cost penalties.

In writing this book, we have drawn upon some 16 years of experience in teaching mechatronics on the Masters courses at Lancaster University and at the University of Abertay Dundee as well as on research programmes covering areas as diverse as construction robotics, systems for the disabled, manufacturing technologies, modular robotics and especially in engineering design. This has also involved extensive involvement with a wide variety of industries from the small to multi-nationals with projects ranging from the design of advanced instrumentation and systems for the disabled to domestic appliances, smart homes, manufacturing automation, safety systems and construction robotics.

A single book covering all aspects of mechatronics would not fit on any conventional bookshelf! Instead, we have structured the text to reflect what we believe are the current significant areas of development in mechatronics and to provide the reader with guidance as to problems and developing techniques in these areas. Thus the book begins in Chapter 1 with a review of the evolution of the mechatronics technologies, of design tools and methodologies and the link to concurrent engineering, Chapter 2 introduces the concepts of machine intelligence and its role in modern mechatronic systems. Chapters 3 and 4 then concentrate on the mechatronic design process and particularly the procedures for requirements interpretation. Chapters 5 and 6 further explore the concepts of artificial intelligence and the applications of neural networks and fuzzy logic in the control and operation of mechatronic systems while Chapters 7 and 8 introduce the reader to software concepts and the human-machine interface. Chapter 9 deals with a particularly important, but often relatively neglected, area of system design and development, that of safety, while Chapter 10 looks at manufacturing technology. Chapter 11 takes a look at the future of mechatronics in a number of areas of technology while Chapter 12 provides a series of short case studies covering various aspects of current mechatronic systems.

A particular theme running throughout the book is the use of the autonomous and robotic excavator, LUCIE, as a running case study to illustrate points made in the various chapters. The LUCIE project began in 1987 at Lancaster and has at some point or other in its development involved all of the authors. It has evolved over the years to a point where it is capable of locating itself on site and of digging a trench, including the removal of certain classes of obstacles from the trench line, without operator intervention. Thus, Chapter 2 contains an introduction to the problems of autonomous trenching while Chapter 4 shows how some of the techniques discussed therein could be applied. In Chapters 5 and 7 the artificial intelligence and software aspects are presented while Chapter 8 considers the operator interface design, with safety aspects being discussed in Chapter 9.

Much of the material in the book is based on lecture notes and other material prepared for the undergraduate, masters and industrial courses with which

we have been associated as well as on research programmes extending over many years. Our thanks therefore go to all those students; undergraduate, masters and doctoral, whom we have taught and worked with for their input in support of the development of much of the material presented. In terms of research, particular mention must be given, but in no particular order, to Rob Bracewell, Patrick Langdon, Les Dungworth, Peter Green, Stephen Quayle, Ajaz Ahmed, Simon Butterworth, Costas Giannopoulos, Jon Goda, Peter Griffith, Richard Walters, Johnny da Silva, Thomas Olbrich, Allan Gardam, Jim Mann, Mark Goodwin, Simon Brownsell, Gareth Williams, Sa'ad Mansoor, Jason Scott, Frank Margrave and Linda Chua.

Thanks must also be given to those companies who have provided material and information for the book and especially to the various people who provided help and advice on its content and structure. Particular mention must be given to Bill Scarfe and Gordon Humphries for their direct and indirect input over many years which helped to ensure that we retained an industrial perspective in our approach to mechatronics.

Finally, but perhaps most importantly, thanks go to Professor Michael French for his help and advice over a period of over 25 years. Michael French founded the Engineering Department at Lancaster University in the late 1960s and was responsible for establishing a design-based, and ultimately mechatronic, culture among both staff and students which culminated in the establishment in 1990 of the Lancaster Engineering Design Centre investigating the development and provision of computer based tools to support the design of mechatronic products. Without his work in creating the environment within which we, the authors, have all at some time worked this book would never have been written.

David Bradley
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Of machines and mechatronics

1

1.1 INTRODUCTION

In 215 BC the Roman general Marcellus led an army to Sicily for the purpose of capturing the city of Syracuse taking with him a range of military technology that included siege towers and a catapult so big that it required eight ships lashed together to carry it. On arriving outside Syracuse, Marcellus discovered that its defences had been augmented by a range of machines devised by the Greek scientist and engineer Archimedes and that assaults were met by a barrage of missiles from giant catapults and by boulders dropped from cranes that swung out over the city walls. Most terrifying were the giant 'claws' that grasped and shook the Roman ships as they tried to enter the harbour. In the words of Pliny:

> 'The ships, drawn by engines within and whirled about, were dashed against steep rocks that stood jutting out under the walls, with great destruction of the soldiers that were aboard them. A ship was frequently lifted up to a great height in the air – a dreadful thing to behold – and was rolled to and fro, and kept swinging, until the mariners were all thrown out, when at length it was dashed against the rocks, or was dropped.'

As to the role of Archimedes, Livy commented:

> 'An operation launched with such strength might well have proved successful, had it not been for the presence in Syracuse at that time of one individual – Archimedes, unrivalled in his knowledge of astronomy, was even more remarkable as the inventor and constructor of types of artillery and military devices of various kinds, by the aid of which he was able with one finger, as it were, to frustrate the most laborious operations of the enemy'.

Archimedes was born in Syracuse around 287 BC. The son of the astronomer Phidias, he studied at the 'Museum' or university in Alexandria that had been founded by King Ptolemy II based on the teachings of Strato the philosopher, the head of the Lyceum in Athens from 287 BC to 269 BC. Following his studies, Archimedes later returned to Syracuse where he acted as adviser to its ruler, Hieron II.

In addition to the war engines referred to above and the discovery of the principle of floatation that carries his name, Archimedes was responsible for a series of developments in mechanics and was reputed to have single handedly launched the Royal ship *Syracusa* when fully loaded using a system of pulleys and levers of his own devising. When Syracuse finally fell, Archimedes was killed by Roman legionaries and was buried with full honours by Marcellus who had inscribed on his tomb a design depicting the ratio between the volumes of a sphere and a cylinder as Archimedes himself had requested be done.

Though the lever, pulley, wedge and windlass were known and in use prior to the end of the 4th century BC and the screw was an invention of the 3rd century BC, traditionally by Archimedes himself, Archimedes was the first of the great scientist/engineers whose works have passed down through history and was one of the first to appreciate and understand the working relationships between men and machines and the ways in which machines could be used to support all areas of human function and activity.

Of others of this early period in the development of the relationship between machines and men, four in particular are worthy of note. The first of these is Ctesibius of Alexandria. A contemporary of Archimedes, Ctesibius lived and worked in Alexandria in the middle of the 3rd century BC and though his writings have been lost he is credited with the invention of a range of mechanisms including a fire engine (Fig. 1.1), a pneumatic 'gun', a water organ and a clock. Slightly later than Ctesibius comes Philo of Byzantium whose work 'On Artillery Construction' dates from around 200 BC and details features such as the use of twisted skeins of material as an energy store as well as experimentation that was undertaken to determine the most effective combination of parameters for artillery. Ctesibius and Philo were followed in the later part of the 1st century BC by Marcus Vitruvius Pollio who in his writings details a range of mechanical systems including developments in artillery, water and wind power and a description of an odometer for measuring distance.

After Archimedes, perhaps the greatest of these early engineers of whom a record has survived is Heron (or Hero) of Alexandria who in the 1st century AD produced descriptions of a series of inventions and mechanisms such as a constant head water clock (Fig. 1.2), a system for automatically opening temple doors (Fig. 1.3), a coin operated dispenser for holy water, a miniature theatre complete with simple automata as the players and many others. Perhaps Heron's best known invention is the aeolopile, a simple steam turbine. Shown in Fig. 1.4 this consists of a large, sealed cauldron of water connected by pipes to a sphere with two opposed nozzles. As the water in the cauldron was heated, steam was transferred to the sphere where it exited via the nozzles, causing the sphere to rotate.

By the end of the 1st century AD in Europe the study of mechanics was well developed and applied, particularly by the Romans, to systems including treadmill operated cranes such as that shown in Fig. 1.5 and the large scale use of water power for milling. By the 5th century, the overshot wheel had appeared while tidal mills were in operation along the Atlantic coast of France and floating mills were reported in operation on the Tiber in the 6th century. Similar developments with water power were also taking place in China though, unlike the Romans, the Chinese used their watermills to drive bellows and trip hammers as well as to mill corn.

Over the next 1500 years however technological progress was to to be relatively slow despite works such as the 'Book of Ingenious Devices' written by the three Ban Musa brothers of Baghdad in the 9th century. This work describes a range of devices including an oil lamp with a self adjusting wick and automata such as the pond surrounded by moving statues of warriors reportedly built for the Caliph at the start of the 10th century. This interest in automata in the Arab world was continued by others including al-Jazari who

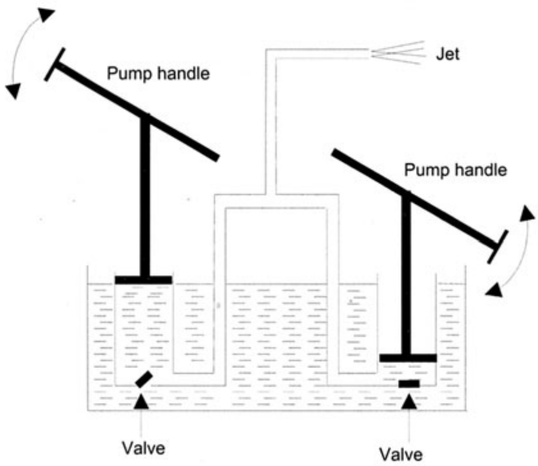

Figure 1.1 Ctesibius's fire engine.

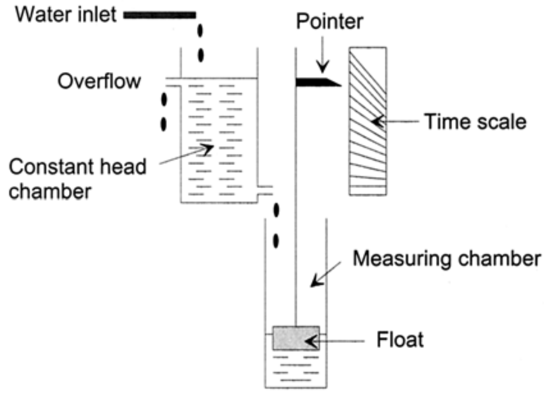

Figure 1.2 Heron's constant head water clock with variable scale for changes in the length of day (from sunrise to sunset).

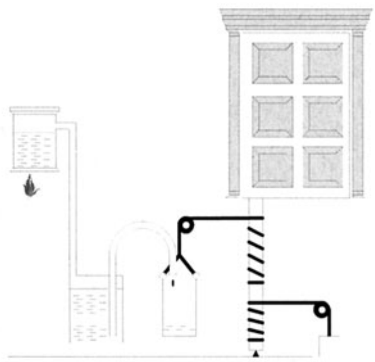

Figure 1.3 Heron's mechanism for opening temple doors.

Figure 1.4 Heron's aeolipile.

in 1206 described clocks that marked the passage of time by using figures to strike drums, blow trumpets or drop stones onto cymbals. Developments in China also included automata and Su Sung's 30 foot high 'Cosmic Engine' built in Hunan in 1090 was powered by a water-wheel and marked the time by figures which moved in and out of doors.

The next great development of scientific thought in Europe took place with the advent of the Renaissance and the work of individuals such as Copernicus, Galileo, Brahe and Leonardo da Vinci. da Vinci in particular turned his attention to many aspects of engineering and technology and has left a legacy of drawings and sketches encompassing subjects as diverse as catapults and crossbows, bridges, the manufacture of cannon, ballistics, lock systems, excavating machines, a water powered saw, gears and gearing, a screw cutting machine, pulleys, ball and roller bearings, power transmission systems, screw jacks, drills, file cutting machines and many others. These individuals were followed in their turn by others such as Pascal, Leibnitz and Newton, each expanding and defining the scientific and mathematical framework on which the industrial revolution of the 18th century was to be based. This

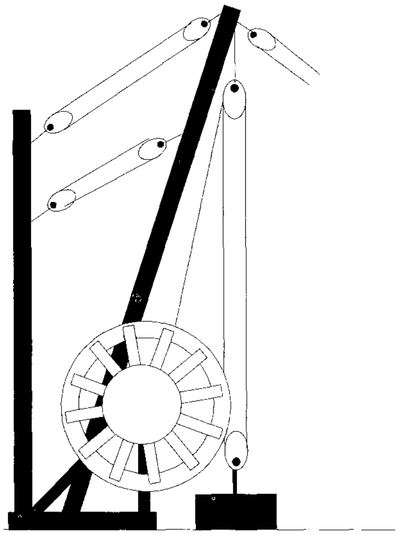

Figure 1.5 Treadmill powered crane.

development and the subsequent growth of technology to the present day is illustrated by Table 1.1 which sets out some of the major technological developments over this period.

Unlike most revolutions, the onset of the industrial revolution was not marked by a single explosive event, or even a series of such events. In Britain it gathered momentum throughout the first half of the 18th century before its main effects began to be felt from around 1760, after which change occurred at an increasing rate. That this was the case may be illustrated by the fact that before this date it was normal to take work to people for it to be done by them in their own homes and yet by 1820 it was usual to bring workers into factories to carry out work under supervision.

The driving force behind much of this change was the availability of a new source of power in the form of the steam engine which, when combined with developments in the technology of weaving, made the concentration of labour into factories the most economic means of production. The demand for greater precision in the manufacture of components for steam engines in turn brought about developments in the manufacturing processes themselves leading to the development and introduction of precision lathes and boring machines. The concentration of manufacturing into factories was also a mechanism for the standardisation of parts and components. Thus, in 1808, Marc Isambard Brunel and Samuel Bentham were able to open a factory in Portsmouth to manufacture pulley blocks for the Royal Navy which replaced the 110 skilled block-makers previously required by 10 unskilled men to supervise the machines.

A further significant development towards the automation of production in the early part of the 19th century was the introduction by Jacquard of a system of punched cards to control the operation of an automated loom, enabling the pattern to be pre-programmed and changed simply by replacing one set of cards by another. The idea of using punched cards to control the operation of a machine was taken up by Charles Babbage who used the idea as the basis of his 'Analytical Engine'. Though this proposed steam powered computer was never built it nevertheless served to introduce many of the concepts that are

Table 1.1 Developments in technology

1452	Birth of Leonardo da Vinci
c1540	A mandolin playing female figure attributed to Giannello Torriano, watch-maker to Emporor Charles V
1543	Copernicus' work on planetary orbits, 'De Revolutionibus Orbium Celestium' is published
c1550	Tartaglia develops the science of ballistics
1610	Galileo uses a telescope to make astronomical observations of the moons of Jupiter
c1642	Blaise Pascale produces his automatic calculator 'La Pascaline'
1614	John Napier publishes his work 'A Description of the Marvellous Rule of Logarithms'
1687	Newton develops his theory of gravitation in 'Philosophiae Naturalis Principia Mathematica'
1694	Leibnitz completes his 'stepped reckoner'
1699	Thomas Savery demonstrates his steam engine to the Royal Society
1700	Development of precision lathes by clockmakers
1709	Abraham Darby establishes his iron foundry at Coalbrookdale
1712	Thomas Newcomen installs his first engine at Dudley, UK. This had a cylinder of 19 inches (48.26 cm) internal diameter and a stroke of around 6 feet (1.82 metres) and at each stroke raised 10 gallons (45.5 litres) of water 153 feet (46.6 metres)
1725	Basile Bouchon devised a silk loom which used holes punched onto a role of paper to control the production of a pattern
1733	The flying shuttle loom invented by John Kay
1738	Jacques de Vaucanson created a flute player capable of playing a dozen tunes
c1740	The introduction of the 'Leyden Jar' as a means of storing charge
c1750	Screw driven tool carriage for lathes introduced by Antoine Thiout
1759	John Harrison completes his marine chronometer No 4 which ultimately led to his being awarded the prize of £20 000 offered by the Board of Longitude, London
1764	James Hargreaves introduces the 'Spinning Jenny' to spin multiple threads
1765	An improved steam engine using a separate condenser is devised by James Watt
1769	Richard Arkwright introduces his water frame spinning machine
1770	Screw cutting lathe developed by Jesse Ramsden
1774	Pierre and Henri-Louis Jaquet-Droz create an automata capable of writing and drawing
1775	John Wilkinson establishes a boring mill in Denbighshire used to manufacture cylinders for Boulton and Watt engines are installed at Bloomfield Colliery in Staffordshire and New Willey in Shropshire, UK
1779	The first iron bridge constructed across the River Severn at Coalbrookdale
	Samuel Crompton introduces the 'mule' combining features of both the Spinning Jenny and Arkwright's water frame
1782	Watt introduces the double-acting steam engine
1784	Oliver Evans introduces a waterpowered automated grain mill outside Philadelphia, USA
1783	The cotton gin is invented by Eli Whitney to comb the seeds from cotton increasing production more than 10 fold
1794	Eli Witney receives the patent for the cotton gin
c1800	Maudslay produces a bench micrometer with an accuracy of 0.0001 inch (0.00254 mm)
19th Century	A variety of 'difference engines' are produced to calculate tables for astronomy, navigation and tides
1800	Maudslay introduces his large screw cutting lathe
	Alessandro Volta describes the 'Voltaic Pile' in a communication to the Royal Society, London
1801	Eli Witney demonstrates principles of mass production to President-elect Thomas Jefferson by assembling muskets from a random set of standard parts
c1804	Joseph Marie Jacquard devised the Jacquard loom which used punched cards to control up to 1200 needles
1808	Marc Isambard Brunel and Samuel Bentham open a plant in Portsmouth to manufacture pulley blocks for the Royal Navy. Driven by a 30 horse power (23 kW) steam engine the machines produced 130 000 blocks a year and replaced the 110 skilled blockmakers previously required by 10 unskilled men

1818 Thomas Blanchard introduces a copying lathe for the manufacture of gun stocks
1819 Hans Christian Oersted observes the deflection of a compass needle by wire carrying an electric current. The relationship is later quantified by Ampere
1821 Michael Faraday demonstrates that a current carrying conductor in a magnetic field experiences a force
1826 Thomas Telford completes his suspension bridge across the Menai Straights, Wales
1829 Robert Stephenson's Rocket wins the Rainhill trials for the Liverpool to Manchester railway
1831 Michael Faraday and Joseph Henry demonstrate electromagnetic induction
1831 Charles Babbage produces the plans for his 'Analytical Engine'
Hippolyte Pixii produces a generator based on Faraday's discoveries
1836 The development of the 'Daniel Cell', the first reliable battery
1837 Samuel Morse obtains a patent for his telegraphy system
Charles Wheatstone and William Cooke install an experimental electronic telegraph system between Euston and Camden Town on the London and North Western Railway
The *Great Western* floated out at Bristol, UK
1838 Cooke and Wheatstone's electric telegraph installed between Paddington and West Drayton on the Great Western Railway
1839 James Nasmyth develops the steam hammer
1840 A remotely controlled dividing engine produced by Henry Gambey is used to graduate a 2 metre mural circle for the Paris Observatory, remains in use until 1920
1843 Morse telegraph is installed between Washington and Baltimore, USA
c1850 Introduction of the turret lathe in America
1853 Production of revolvers by Samuel Colt used 1400 machine tools
1856 Patent granted to Henry Bessemer for the 'Bessemer Converter' to produce steel from pig iron
Friedrich von Siemens patents the regenerative furnace
Ernst Werner von Siemens patents a practical electric generator
1857 The *Great Eastern* is launched on the Thames
1862 Brown and Sharpe introduce the first true universal milling machine
c1865 Introduction of automatic screw cutting lathes in America
1866 The first successful trans-Atlantic cable is laid by the *Great Eastern*
1876 Alexander Graham Bell demonstrates the telephone
1877 Thomas Alva Edison demonstrates the phonograph
1879 Practical electric lighting demonstrated by Edison and Swan
1880 Edison opens a power generating station at Holborn Viaduct in London
1881 Frederick W. Taylor begins studies on the organisation of manufacturing operations at Midvale Steel Company
Frank B. Gilbreth and Lillian M. Gilbreth use 'motion picture' technology to analyse worker's movements and work areas
1882 The Edison Electric Illuminating Company power generating station at Pearl Street in New York begins operation. By mid-1883 it is supplying 431 customers
1885 The first petrol driven automobile built by Karl Benz
1887 First patent for a gear hobbing machine taken out in America
1889 Sebastian Ziani de Ferranti opens a power station at Deptford, London, operating at 10 volts
1890 Herman Hollerith wins the competition held by the US Census with a system which used punched cards to record and sort data
1895 Wireless telegraphy invented by Guglielmo Marconi
1897 Charles Parsons demonstrates the steam turbine ship *Turbinia* at Queen Victoria's Diamond Jubilee Review at Spithead
1901 Marconi transmits a radio message across the Atlantic
1903 Orville and Wilbur Wright make the first sustained powered flight
1904 The vacuum tube is developed by Fleming
1906 Lee De Forrest adds a control grid to Fleming's valve to produce the triode valve
1908 Ford Model T introduced. In 1909 it costs \$950 falling to \$360 by 1916 and \$290 in 1920
General Motors founded
1909 Bakelite announced by its inventor, Leo Hendrik Baekeland

	Louis Bleriot succeeds in flying across the English Channel
c1910	Mechanical analogue computers are developed for naval gunnery control
1913	Henry Ford introduces the production line for the manufacture of the Model T
1919	First trans-Atlantic flights
1920	Karel Capek writes the play 'Rossum's Universal Robots'. The Czech work 'robota' means servitude or forced labour
1920–1930	Widespread introduction of live radio in the United States and Europe
1930	Vannevar Bush develops a 'differential analyser', the first electrical analogue computer
	A patent for a jet engine is taken out by Frank Whittle
1935	Robert Watson-Watt begins the series of experiments which were to result in the development of radar
	The first jet propelled aircraft is flown in Germany
1936	The BBC launches the first public televison service
1939	The development of the cavity magnetron by Randall and Boot enabling centrimetric radar
1940	Isaac Asimov published the first of his robot stories in 'Super Science Stories'. Asimov went on to develop the 'Three Laws of Robotics'
	Nylon and Terylene, the first synthetic fibres produced commercially
1944	Colossus, the first electronic digital computer, enters service at Bletchley Park for cryptography
1945	The first atomic bombs are exploded
1946	The Electronic Numerical Integrator and Calculator (ENIAC) enters service. Designed by J. Presper Eckhert and John W. Mauchly ENIAC weighed around 30 tonnes, occupied a room 9 metres by 15 metres and used some 18 000 vacuum tubes, 70 000 resistors, 10 000 capacitors and 6000 switches
1947	The Bell X-1 flown by Charles Yeager breaks the sound barrier
1948	Baby, the first true stored programme computer, developed at Manchester University in the UK
	The transistor is developed at Bell Laboratories by John Bardeen, Walter H. Brattain and William B. Shockley
	George C. Devol develops a controller which used information recorded on magnetic tape to operate a machine
1951	Work on teleoperated manipulators for the nuclear industry for handling radioactive materials
	The Ferranti Mark 1 becomes the world's first commercially available computer
1952	A prototype numerically controlled machine is demonstrated at Massachusetts Institute of Technology
	Colour television broadcast using the NTSC system begins in the United States
1956	FORTRAN, the first high level computer language, appears
1957	Sputnik 1, the first artificial satellite, is launched
1958	Texas Instruments introduce the first commercial integrated circuit
1959	Planet Corporation introduces the first commercial robot based on limit switches and cams
1960	The first Unimate hydraulically driven robot is introduced. This is based on Devol's 'programmed article transfer' system and used numerical control
	T. H. Maiman produces the first laser
1961	A Unimate robot is installed by Ford to service a die casting machine
	The part programming language APT (Automatically Programmed Tooling) is released
	Yuri Gagarin becomes the first man in space
1962	Telstar I, the first commercial communication satellite, is launched
1963	The American Machine Company introduces the Versatran robot
1966	In Norway, Tralfa design and install a paint spraying robot
	Colour television broadcasts using the PAL system begin in Europe
1968	Burroughs produces the first computers to use integrated circuits
	Stanford Research Institute introduce a mobile robot. Named 'Shaky' this robot was equipped with a range of sensors including a camera and a rangefinder enabling it to find its way around a room. Communication with the main computer was by radio
1969	The US Department of Defense introduces Arpanet, the forerunner of Internet
	Apollo 11 lands on the moon

1971 A small electrically powered robot arm is developed at Stanford University
1972 The first colour VCR is introduced
The first 8-bit microprocessors appear on the market
1973 Large Scale Integration with 10 000 components on a 1 sq-cm chip
Stanford Research Institute demonstrates the WAVE programming language. This was followed in 1974 by AL. The two languages were merged into the VAL language by Unimation
1974 ASEA introduce the all electric drive IRb6 robot
Kawasaki install arc-welding robots for the production of motorcycle frames
'The Tomorrow Tool', better known as the T3 robot, is introduced by Cincinnati Milicron
UNIX computer system described in the Communications of the Association for Computing Machinery
1975 A Sigma robot from Olivetti is used in an assembly operation, an early example of this type of operation
1976 The first Cray-1 super computer delivered to Los Alamos Laboratory
Viking spacecraft land on Mars
Whitfield Diffie, Martin Hellman and Ralph Merkle define the basis of public/private key encription
1977 Apple Computer introduces the Apple II, the first personal computer incorporating a keyboard and power supply to generate colour graphics
CompuServe goes on line
Ronald Rivest, Adi Shamir and Leonard Adelman define the RSA algorithm for public/private key encription
1978 The PUMA (Programmable Universal Machine for Assembly) is introduced by Unimation
A T3 robot is used for drilling and routing operations as part of the US Air Force Integrated Computer Aided Manufacturing programme
16-bit microprocessors introduced
1979 The SCARA (Selective Compliance Arm for Robotic Asembly) arm is developed at Yamanshi University in Japan
1980 Intel introduce the first 32-bit microprocessor
Telenet introduces a commercial computer networking service
1981 IBM introduce a personal computer with an industrial standard disc operating system (DOS)
Carnegie-Mellon University demonstrates a direct drive robot using electric motors located at the joints
Sony introduce the Walkman personal stereo system
1982 IBM introduces the RS-1 assembly robot
Hewlett-Packard introduce the first 32-bit personal computer
Institute for New Generation Computer Techniques established in Japan to investigate 'fifth-generation' computer systems
1983 Motorola receive the licence for the first cellular telephone system in the USA
Cray Research introduce the Cray X-MP supercomputer
1984 Philips and Sony develop the compact disc read-only memory (CD-ROM)
Apple Computers introduce the Macintosh computer system
Introduction of CMOS technology for integrated circuits (ICs)
Sumitomo demonstrates an organ playing robot developed at Waseda University in Japan
1985 The equivalent of 300 000 telephone calls are transmitted using an optical fibre
1987 Integrated Services Digital Network extends the scope of its field trials
The number of subscribers to cellular systems reaches 1000 000
1988 Intel introduce the 80386 processor
SUN Microsystems introduce the SUN 4 based on the use of a Reduced Instruction Set Computer (RISC) processor
IBM introduce the PS/2 personal computer together with the OS/2 operating system
1990 The World Wide Web is set up on the Internet by Tim Berners-Lee at the European Particle Physics Laboratory in Switzerland
Intel introduce the i860 chip
Hewlett-Packard introduce workstations based on the Precision Architecture-Reduced

	Instruction Set Computer (PA-RISC) processor
1991	Thinking Machines introduce the massively parallel CM-5 computer
1993	Sun introduce the SPARCstation 10 capable of being configured around multiple CPUs
	Subscribers to cellular systems reach 10 000 000
1993	Intel introduce the Pentium processor
	Mosaic, a free software program, is introduced to search the World Wide Web
	Apple introduce the Newton using a 'write-on' screen instead on a keyboard
1994	Netscape creates its Navigator software for browsing the Internet
	Digital Satellite System provides up to 175 TV channels
	IBM and Apple introduce the Power Mac
	DEC introduces the Alpha processor operating at 275 MHz
1995	Microsoft launch Windows 95
1997	Intel launch the Pentium II processor
	Pathfinder mission lands the Sojourner vehicle on Mars
1998	Microsoft introduce Windows 98
	450MHz Pentium II processors available
	Digital television introduced in UK
	Work begins on the construction of the first permanent manned Earth orbital station
	Apple introduce the iMAC computer
1999	Bluetooth 1.0 specification for wireless communication of data and voice released
	High performance flat screen desktop displays available
	700 MHz plus processors available
	Sony produce a robot 'puppy' which responds to commands and can 'play' with a ball
	Dyson introduces a robot vacuum cleaner
2000	The 'Millennium Bug' fails to appear

found in modern computers including the ideas of a program containing both instructions and data and a processing unit in which the data is manipulated according to the instructions contained in the program. Babbage's work was followed by the development of a number of hand operated 'difference engines' used for the calculation of tide tables, planetary motion and insurance rates. Then, in 1890, Herman Hollerith won a contract from the US Census Office to produce an electrically operated sorting machine working with punched cards to collate census data, thus founding IBM.

Though levels of industrial automation were to increase steadily throughout the 19th century, perhaps the most significant developments took place in another area of technology, that of electricity. Although static electricity and its effects had been known for centuries, it was only with the development by Volta of the 'voltaic pile' at the end of the 18th century that a ready source of electricity became available. Driven by the experimental work of Faraday, Henry and others, the first half of the 19th century saw dramatic developments in this new science such that by the time of the Great Exhibition in London in 1851, telegraph systems were common and experiments with arc lighting were underway. The final years of the 19th century saw electricity establish itself as a major technology with the establishment by Edison, Siemens, Ferranti and others of generating stations in London, New York and elsewhere and the development by Edison and Swan of practical electric lighting systems.

Developments in technology continued to gather pace in the later part of the 19th century and the early part of the 20th century, a period which saw the introduction of the motor car, aircraft, radio, mass production and, perhaps most significantly of all, the vacuum tube valve; this later enabling the development by Vanevar Bush in 1930 of the first electronic analogue computer.

By 1930 the many of the technologies that were to drive the second half of the 20th century were in place but were still essentially separate, existing within their own individual context and with relatively little interaction. The decade leading up to the start of World War II did however see a number of further major developments in electronics including the early experiments in radar, the first public television service and the development of the magnetron. Also, in 1940 Isaac Asimov published the first of his robot stories, leading eventually to the introduction of the 'Three Laws of Robotics' which for the first time defined a behavioural framework for intelligent, human-like machines.

Electronics made a major contribution to the conduct of World War II in the form of both radio and radar and led to the growth of 'electronic warfare' as each side tried to intercept or jam their opponents communications networks. A major, secret, battle was also fought to break and read the codes and cyphers used by both sides as for instance the messages generated using the Enigma machine and its variants and later by the Gehieimschreiber or 'secret-writing machine', code named 'Fish' by the Allies. These efforts led in turn to the introduction at Bletchley Park in the UK in articular of a series of special code-breaking 'computers'.

The first of these were the 'bombes' whose task was to analyse intercepted messages to determine, by what was essentially a process of trial-and-error, the wheel settings for the Enigma machine. The bombes were 'programmed' by means of 'menus' generated by the operating staff using 'cribs' based on other intercepted messages to provide an initial guess at the current settings.

The first attempt a deciphering messages generated using the Fish machine, which used a random binary sequence as the basis of its encryption process, was a machine known at Bletchley Park as 'Heath Robinson', after a well-known cartoonist of the time. This used some 80 valves and suffered from a range of operational problems leading to its replacement in 1943 by the machine known as Colossus. This was the worlds first electronic computing system and in its original version used some 1500 valves, a number which was to rise to 2500 in later versions. Programming was interactive by means of switches and a plugboard and by the end of the war operation of the number of Colossi then in service involved some 20 cryptanalysts, 20 engineers and over 250 operators. Included their number was the mathematician Alan Turing who pre-war had determined the basic structure of a programmable, stored program computer.

The first two decades following the end of World War II saw electronics gradually establish itself as perhaps the dominant technology, impacting on all aspects of industry and home life. The development of the transistor in 1948 by Shockley, Bardeen and Brattain coincided with the entry into service of the Electronic Numerical Integrator and Calculator (ENIAC). Intended for ballistic calculations, ENIAC occupied a room 9 metres by 15 metres and used some 18 000 vacuum tubes, 70 000 resistors, 10 000 capacitors and 6000 switches. ENIAC was followed two years later by the development at Manchester University in the UK of the first true stored program computer. Developed by a team led by F.C. Williams and including Turing, their work led directly to the introduction in 1951 of the world's first commercial computer, the Ferranti Mk I.

At the same time that computers were finding their feet, developments in manufacturing automation were beginning which were to lead ultimately to the integration of computers with machine tools and the subsequent growth of mechatronics. By the mid-1950s, the first numerically controlled (NC) machines were appearing in industry and by the end of the decade the first viable commercial robots were under production by Unimation, the company formed by George C. Devol and Joseph Engleberger. The first major commercial application was in 1961 by Ford to service a die casting machine.

Also by this time the first integrated circuits, combining multiple transistors and other components onto a single chip, had started to appear and the first satellites had been launched, including in 1961 the first commercial communications satellite, Telstar I. Development of electronics technologies continued throughout the 1960s. However, although the first computer based on the use of integrated circuits had been introduced by Burroughs in 1968, the discrete transistor still formed the basis of most electronic systems at the end of the decade.

The development in the early 1970s of the large scale integration (LSI), enabling by 1973 the incorporation of 10 000 components onto a 1 square centimetre chip, led directly to the introduction of the 8-bit microprocessor. By 1980, 'home computers' such as the Apple II were available and 16-bit microprocessors were being produced. These were followed in 1980 by the introduction by Intel of the first 32-bit microprocessor while in 1981 IBM introduced the first personal computer (PC). Over the same period minicomputers such as the PDP-8 and PDP-11 produced by the Digital Equipment Corporation were increasingly being used for control purposes in industry leading in turn to the introduction of computer numerically controlled (CNC) machine tools. Dedicated microprocessors were also being used to control the operation of an increasing range and number of systems, both at home and in industry.

Throughout the period of the 1980s and 1990s, the technologies of electronics and computing resulted in more and more processing power becoming available in the form of advanced processors such as the Pentium of Fig. 1.6. The result is that there are now few items which are not designed using computers or which do not deploy computers, microprocessors or microcontrollers in some way in support of their operation. This integration of the technologies of electronics and software with mechanical engineering is referred to as mechatronics and offers the design engineer the opportunity not only to improve the performance of existing systems such as cars and aircraft but enables the introduction of new products and systems such as the compact-disc (CD) player which would not be achievable by conventional means.

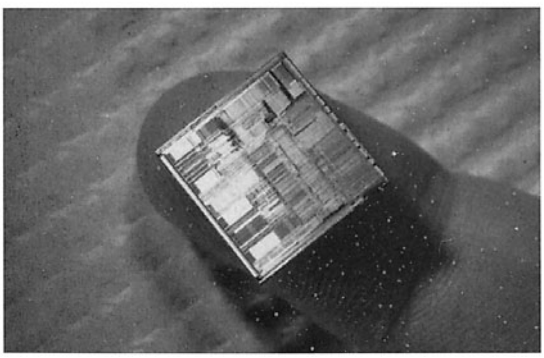

Figure 1.6 Pentium processor chip. (*Courtesy of Intel.*)

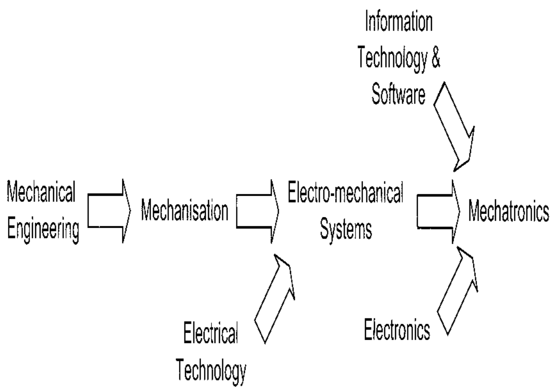

Figure 1.7 The evolution of mechatronics.

1.2 MECHATRONICS AND TECHNOLOGY

Mechatronics provides both a title and a focus for the design and development of a wide range of engineering systems, both products and processes, in which the technologies of electronics, software engineering and information systems are integrated with mechanical engineering. The resulting combination of what have until relatively recently been considered as separate, and often competing, disciplines and the associated transfer of functionality between solution domains has been responsible for the appearance of systems in which the previous, essentially mechanical, solutions have been replaced by ones based on the integration of electronics and software with the mechanical functions.

In considering the technical development of mechatronics suggested by Fig. 1.7 it is important to note that the general structure and concept of mechatronics and mechatronic systems as represented by Fig. 1.8, in which the system is separated into an energetic and an information domain together with a world interface, can exist at a variety of levels. Consider for instance the manufacturing system of Fig. 1.9(a). This can be redrawn in the form of the context diagram of Fig. 1.9(b) from which it is seen that the nature and characteristics of the mechatronic system remain the same whatever the viewpoint adopted, only the scale changes. Thus, for instance, the world of a robot joint, which may itself constitute a mechatronic system in its own right, is the robot itself, while the world of the robot is the manufacturing cell of which it forms a part. The world of the manufacturing cell is then the factory.

As well as integration, a feature of many mechatronic systems is their transparency of operation when in use. Thus, the driver of a car with an advanced engine management system has no direct perception of its operation other than in terms of the improvement in performance that results. The effect of this transparency of operation and the associated devolution to the system level of responsibility for its functional behaviour is that the operator or user of a

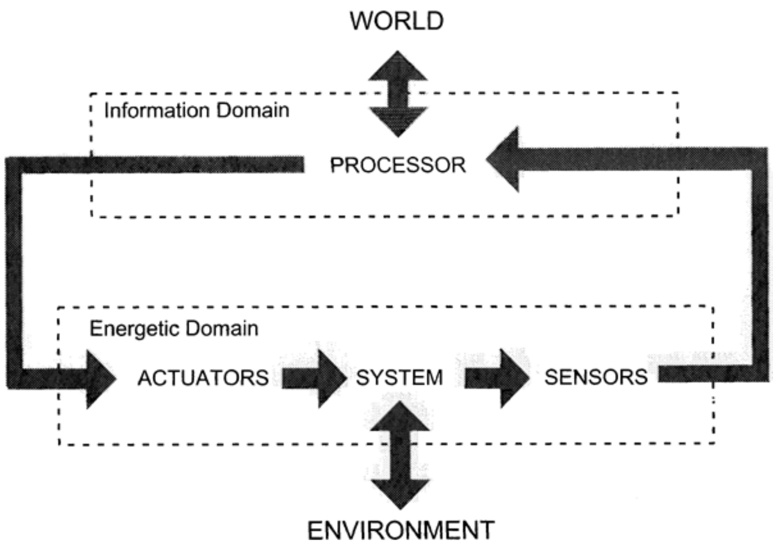

Figure 1.8 A generalised mechatronic system.

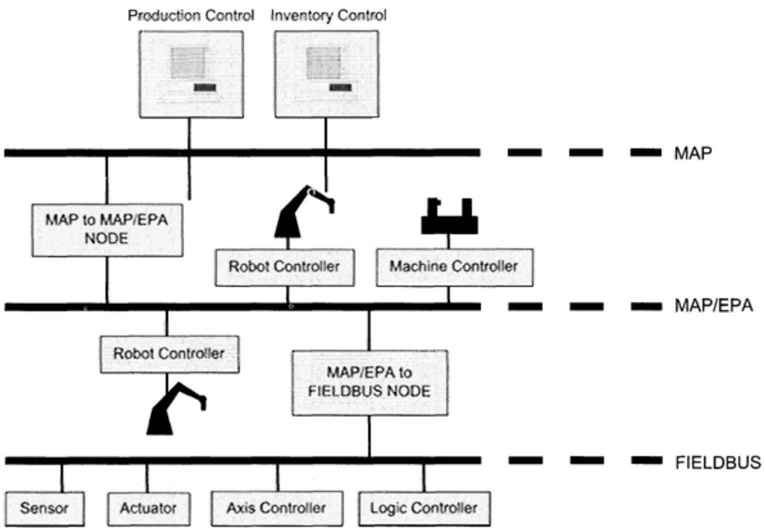

Figure 1.9a Manufacturing systems communication hierarchy.

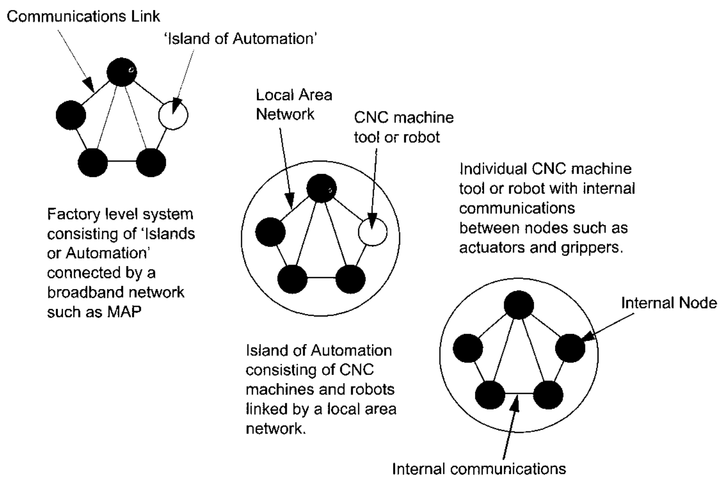

Figure 1.9b Manufacturing system context diagram.

mechatronic system is free to concentrate on the higher level functions associated with its use.

This can be illustrated by reference to the functional diagram of an automatic, autofocus reflex camera with interchangeable lenses shown in Fig. 1.10 in which each of the major 'hard' elements of the system; body, lens and flashgun, constitutes a mechatronic system in its own right. From the point of view of the user, once the appropriate operating mode has been selected the process of determining the required combination of aperture and shutter speed and of maintaining focus becomes the responsibility of the camera. The user is therefore freed to concentrate on achieving the desired composition. Changing part

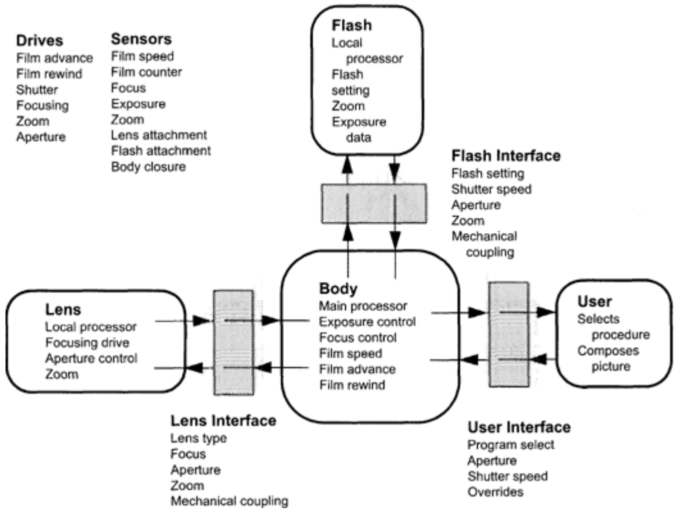

Figure 1.10 Camera system.

of the system, for instance by replacing a lens with one of a different focal length, is automatically recognised by the system and the internal set up modified accordingly.

The major characteristics of an intelligent mechatronic system can therefore be summarised as:

- generally complex systems exhibiting high levels of integration;
- increased functionality with respect to conventional systems;
- transfer of function from the mechanical to the electronics and software domains;
- system assumes responsibility for process allowing operator to concentrate on procedures;
- distributed processing with devolved intelligence;
- multi-sensor environment;
- system operation generally transparent to user;
- multi-program environment with user selection.

In order to further understand the development and importance of mechatronics, the fundamental technologies involved in the development of both the concept and the practice need to be considered.

1.2.1 Basic mechatronics technologies

Microprocessors and integrated circuits

The development of intelligent and mechatronic systems has been supported by increases in the performance, at reducing real costs, of electronics and processing power which has in many cases led to the development of dedicated controller architectures based on the use of microprocessors, microcontrollers and application specific integrated circuits (ASICs). Unfortunately, the improvements in the performance and cost of processing power have not necessarily been paralleled by similar developments in the cost of sensors and actuators, as suggested by Fig. 1.11.

For mechatronic applications, there is a fundamental need for interface electronics functioning in relation to the sensors and actuators. Both of these elements require an analogue circuit capability and in the case of actuators there will be a power requirement at the output stage. In addition, local processing, transparent to the remainder of the system, may well be incorporated to shape individual device characteristics.

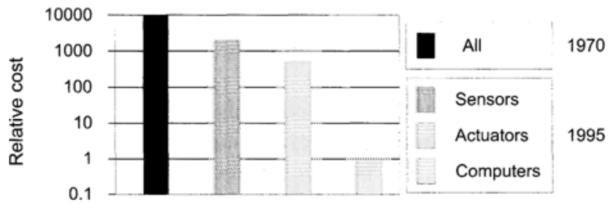

Figure 1.11 Changes in the relative costs of sensors, actuators and computing power, 1970 to 1995.

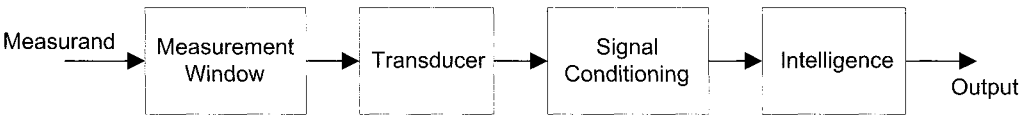

Figure 1.12 The basic structure of a smart sensor.

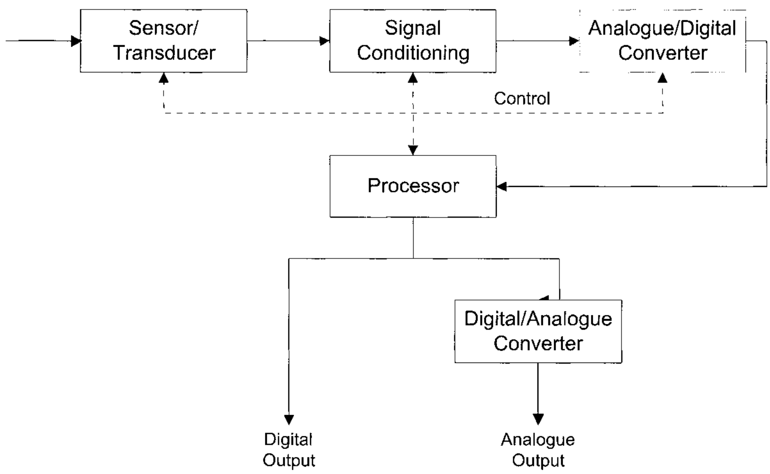

Figure 1.13 The architecture of a smart sensor.

In electronics, advances in computer aided design and simulation have increased access to on-chip solutions across a wide range of circuit types and applications. These application specific integrated circuits (ASICs) are playing an increasingly important part in the development of mechatronic systems, resulting in a growing need to integrate the design of ASICs and other electronic elements more fully into the overall system design process.

Sensors and sensing

In an intelligent mechatronic system, sensors are used to provide information about both system and world conditions and as engineering systems of all types become more mechatronic in nature, the demands on sensors and the associated signal processing will continue to increase. The expansion of silicon technology and the growth of silicon micromachining is leading to the development of low cost, high performance sensors which will, in turn, make possible new developments in intelligent systems which will place an increased emphasis on the incorporation at the sensor level of local signal processing and the ability to communicate with other sensors and sub-systems. A typical configuration for such a 'smart sensor' is shown in Fig. 1.12 while Fig. 1.13 suggests one possible architecture for such a sensor.

In safety critical areas such as flight control systems or car airbags it is important to ensure system reliability and performance integrity. In terms of the sensors and sensing systems this means the incorporation at the chip level of built-in-self-test (BIST) structures together with increased support for sensor, data and system validation processes.

Actuators

While the most common actuators for mechatronic applications are based on conventional and established technologies such as electric motors, including servomotors and stepper motors, fluid power and mechanical drives other forms of actuator are becoming increasingly available. These include:

Ultrasonic or piezoelectric motors
These typically use an array of piezoelectric elements to create a travelling wave which interacts with a friction plate to produce motion. Applications include camera focusing drives and micropositioning systems.

Micromotors
Created by the micromachining of silicon, micromotors with dimensions of the order of a few hundred microns have been produced with possible applications in medical instruments, office and domestic equipment and cameras.

Piezoelectric actuators
Piezoelectric actuators are capable of providing high forces over small distances with fast response times. Though the range of movement is generally too small for most applications this can be amplified by means of levers and hydraulics. Applications include micropositioning systems, inkjet printers and Braille output devices.

Magnetostrictive actuators
Magnetostrictive actuators utilise the dimensional change that occurs in certain materials when subject to a magnetic field. Performance and applications are similar to piezoelectric actuators.

Shape memory alloys
A shape memory alloy will move between a current state and a 'remembered'

state in response to temperature variations. Applications include positioning systems and transfer devices.

Information structures

Figure 1.14 shows in simplified form a possible information structure for a hierarchy of mechatronic systems. Within this structure, the information contained can be considered in terms of that which is associated with a particular level within the system and is therefore concerned with the process or processes carried out at that level together with a vertical flow of procedural data between levels.

In terms of Fig. 1.14, process data is concerned with the level of the system at which it is generated and may be either active, in which case it is directly associated with the control of the process being executed, or passive in which case it plays no part in normal operation, for instance an alarm. Examples of process data at the plant level of Fig. 1.14 would include the co-ordination of the operation of the machine tools and robots making up a manufacturing cell while the operation of the individual machine tools and robots is defined at the servo-control level.

In the context of Fig. 1.14, procedural data flows vertically between levels and can range from being highly-conditioned to ill-conditioned in form. Highly-conditioned procedural data is bounded and contains all the data necessary to define the process or processes to be executed at any particular level. For example, in a manufacturing cell, the task definition for the cell provides the procedural data necessary to establish the processes to be carried out by an individual machine tool or robot. On the other hand, ill-conditioned procedural data contains either or both of redundancies or omissions and requires interpretation by the receiving agent. This is particularly the case involving communications between humans where reliance is often placed on the understanding and knowledge of the parties involved to interpret the transmitted data correctly. The ability to deal with incomplete data using a heuristic approach based on a combination of knowledge, experience and understanding is inherent to much of human intelligence and similar structures will be required at the human–machine boundary if an effective human–machine collaboration based on an understanding and sharing of their individual capacities and capabilities is to be achieved.

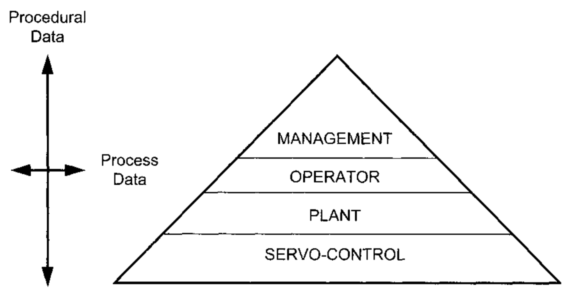

Figure 1.14 The relationship between procedural and process data in a mechatronic context.

Communications

Communications, and particularly digital communications, form an essential component of mechatronics as the means by which information of all forms is transferred between the individual system elements and sub-systems. Communications systems would typically be based on the International Standards Association (ISO) Open Systems Interconnection (OSI) model of Fig. 1.15.

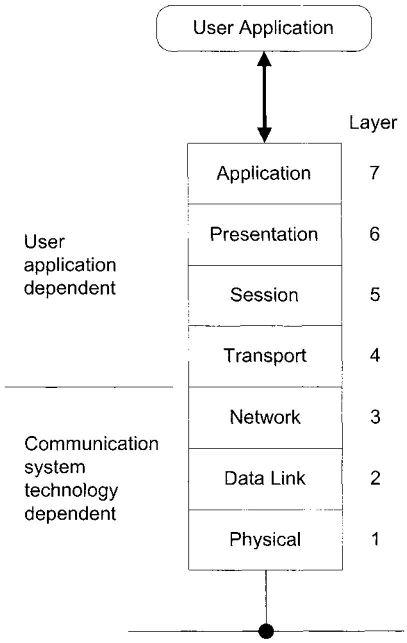

Figure 1.15 OSI/ISO seven layer model.

Control

Table 1.2 shows that the behaviour of intelligent mechatronic systems must be considered at several levels, and an appropriate control strategy is therefore required for each level. Additionally, the control strategy adopted must take account of the fact that each of the levels in the control hierarchy operates on a different time scale and to a different spatial resolution with respect to the other levels. This temporal and spatial separation is necessary to ensure safe and consistent operation. Further, it has been postulated that at each higher level:

Table 1.2 Levels of control and operation for intelligent machines

Strategic level	User specified production goals
Tactical level	Production goals are analysed to establish specified goal
Task level	Define tasks to be completed in relation to the specified goal
Action level	Decompose individual tasks into an appropriate sequence of actions
Trajectory level	Define the motion path required from the current position
Servo level	Decompose actions into the drive commands for individual joints

- control bandwidth decreases by about an order of magnitude;
- perceptual resolution decreases by about an order of magnitude;
- planning horizons increase by about an order of magnitude;
- planning models decrease in resolution and expand in range by about an order of magnitude.

For instance, a time constant of about 300 ms may well be appropriate for a heavy manipulator and this response time can be achieved by a servomotor with a sampling interval of about 30 ms and a command update interval of about 3 ms. Considerations of this kind lead to relationships such as those in Table 1.3 for the temporal and spatial resolution required at each level. Similar relationships can be defined for other types of system.

Table 1.3 Temporal and spatial resolution requirements for different levels of control

Control level	*Event detection interval(s)*	*Spatial resolution (mm)*
Task	30	3000
Action	3	300
Trajectory	0.3	30
Servo	0.03	3

Also in the area of control, the development of robust control strategies at the actuator level are being combined with high level, real-time artificial intelligence (AI) based structures, perhaps involving neural networks and fuzzy logic, to enable systems to assume an increasing degree of responsibility for their own actions. The operation of such goal oriented, task driven systems may also be integrated with operator control through the provision of appropriate interfaces to reduce the load on, or to provide additional functionality to, the operator.

Software

The provision of properly structured software is essential to the operation of an intelligent mechatronic system as it is in the software that flexibility and capability of the system generally resides. For instance, in the case of the 'software cam' of Fig. 1.16 the response characteristic is readily modified by changing within the software the parameters defining the desired motion profile.

In many applications, the cost of the software development forms a major, if not *the* major, cost component, requiring careful attention to and control of the software definition, planning and development processes. Well engineered software should:

- be written and documented so as to support, at minimum cost, development and maintenance over its life;
- have reliability built in to its design and coding;
- be as efficient as possible without adding complexity and hence increasing maintenance costs;
- support appropriate user interfaces.

In a mechatronic system, the software specification and design must be integrated with that of the electronic and mechanical elements, ensuring the appropriate 'transfer of functionality' between the individual domains.

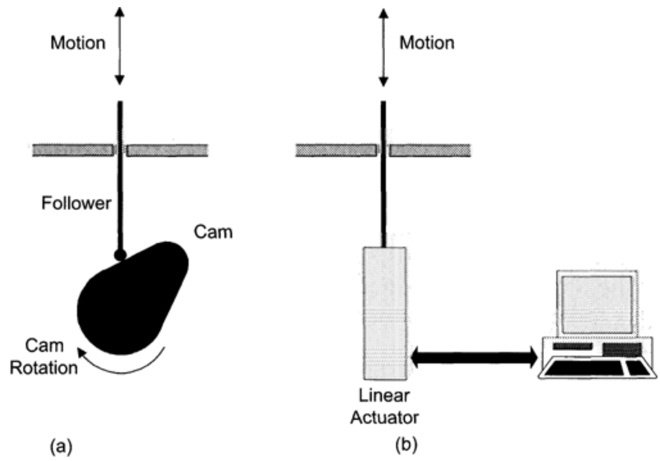

Figure 1.16 The software cam.

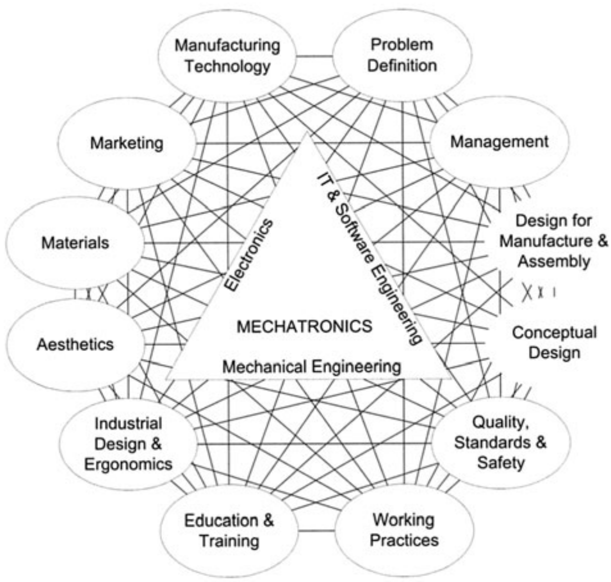

Figure 1.17 Mechatronic relationships.

1.3 ENGINEERING DESIGN AND MECHATRONICS

'.... design is taken to mean the process of conception, invention, visualisation, calculation, marshalling, refinement and specifying of details which determines the form of an engineering product.' M.J. French, *Conceptual Design for Engineers*, The Design Council

'Total design is the systematic activity necessary, from the identification of the market/user need to the selling of the successful product to satisfy the need – an activity that encompasses product, process, people and organisation.'

S. Pugh, *Total Design*, Addison-Wesley (Reprinted by permission of Addison-Wesley Longman)

To make effective use of the opportunities presented by a mechatronics approach to product design and development presents a challenge both to engineering designers and the design process itself. Though the technological basis of mechatronics lies in the integration of mechanical engineering, electrical and electronic engineering with software engineering and information technology, the successful implementation of a mechatronic approach to product design and development requires the bringing together of a much wider range of factors as implied by Fig. 1.17. This in turn requires a company level commitment in order to put the necessary elements into place.

The importance of design to the success of a product is illustrated by Fig. 1.18 and Tables 1.4 and 1.5 in which the balance between the commitment of expenditure during the design phase is compared with the actual spend, primarily during the pre-production and production phases, at which later point the costs of changes to the design increase rapidly.

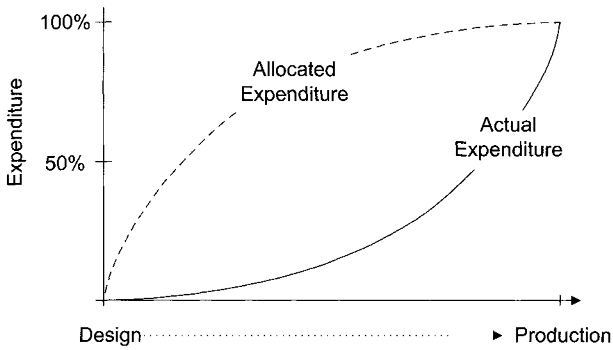

Figure 1.18 The relationship between allocated and actual expenditure from design to production.

Engineering design may be considered as a goal-oriented problem-solving exercise which has as its objective the conversion of a need, often expressed in the first instance as an abstract concept in terms of general functionality, into a product. As suggested by French, the design process can be represented by Fig. 1.19 by a conceptual phase during which possible solutions are considered and an embodiment phase in which the chosen solution is implemented. The associated problem solving process typically follows the path shown in Fig. 1.20 during which the designer may be supported in the development and evaluation of ideas and concepts by a variety of tools and techniques, some of which are also identified in Fig. 1.20.

Other forms of design process model have been suggested such as those by Meister, Ballay, Hubka and Rodenacker set out in Fig. 1.21. In addition, Hansen has attempted to position design in relation to politics, science, art and production as in Fig. 1.22.

However, the very generality of mechatronics across a wide range of engineering systems and environments raises questions in relation to the mechatronics design process, particularly:

- Do there exist certain principles or features of a mechatronic product

Table 1.4 Product development costs

Product development phase	Percentage of total cost (cumulative) Incurred	Committed
Conceptual Design	3–5	40–60
Design Embodiment	5–8	60–80
Testing	8–10	80–90
Process Planning	10–15	90–95
Production	15–100	95–100

Table 1.5 The cost of design changes

Time change is made	*Relative cost*
During design	1
During testing	10
During process planning	100
During pilot production	1 000
During final production	10 000

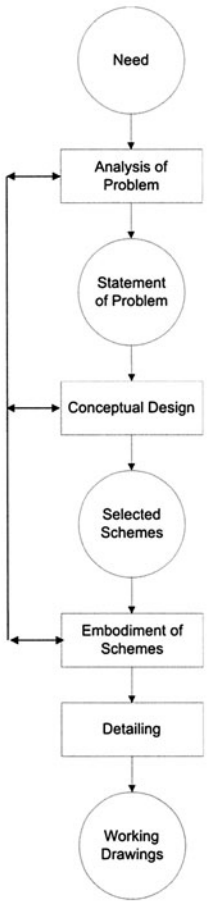

Figure 1.19 French's design model.

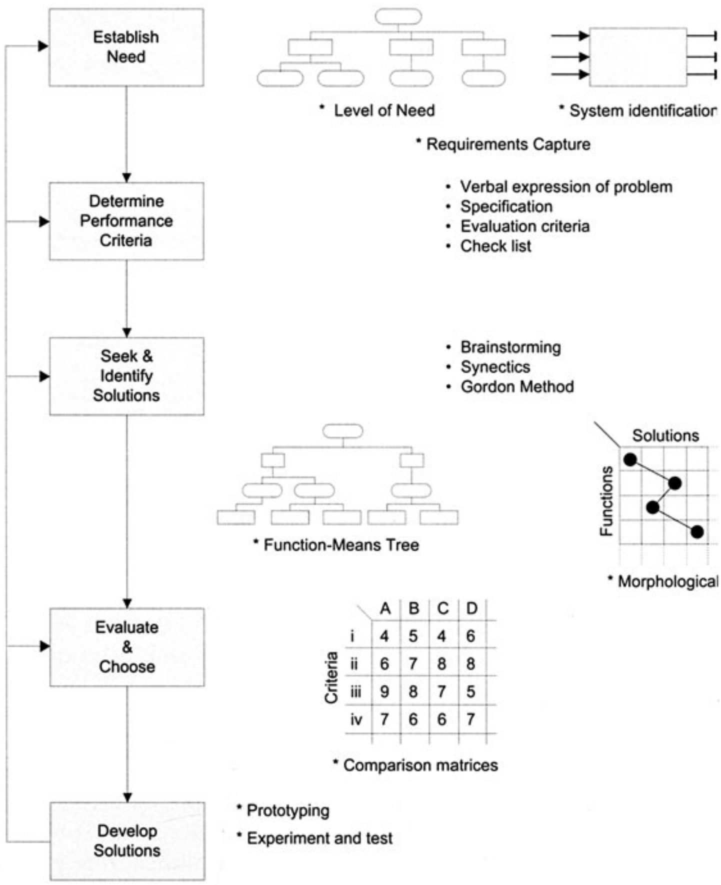

Figure 1.20 Problem solving in design.

which are valid across a range of different markets, products and environments?

- Are such features of themselves the means of gaining a competitive advantage from a mechatronic approach to product design and development?

Meisler's Conceptual Model	Ballay's Sequential Model	Hubka's General Procedural Model	Rodenaker's Structural Model
1. Formulation of the design process. 2. Generation of alternative design solutions. 3. Analysis and evaluation of alternatives. 4. Selection of preferred alternative.	1. Criteria Formulation Collect and analyses information to establish design criteria. 2. Information Transformation Translate information into written briefs, drawings, etc. in a format that can be used for problem solving. 3. Concept Generation Decisions affecting function, fit, aesthetics, etc. 4. Detail Refinement Engineering refinement of previously defined concepts and decisions. Merging of concepts with aesthetic criteria. 5. Release Package Produce and assemble final document for release.	1. Elaboration of assigned processes. 2. Conceptual design. Establish: (a) Functional structure. (b) Design concepts. 3. Laying out. Establish: (a) Preliminary layout. (b) Dimensional layout. 4. Detailing and elaboration.	1. Clarify task. 2. Establish function structure. 3. Choose physical processes. 4. Determine embodiment. 5. Check logical, physical and constructional relationships. 6. Eliminate disturbing factors and errors. 7. Finalise overall design. 8. Review chosen design.

Figure 1.21 Design process models.

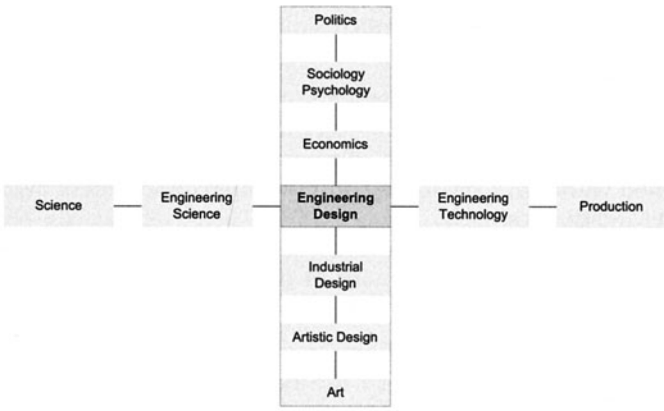

Figure 1.22 Positioning engineering design.

It must also be remembered that the motivation of a move by a company towards mechatronics is that of obtaining a strategic and commercial advantage, either by enhancing the performance or manufacture of an existing product, by gaining access to and developing new markets or by some combination of these. If therefore the answers to these questions is 'yes', then it is likely that the adoption of a mechatronic strategy will be of benefit to a company.

1.3.1 Design models and mechatronics

From the foregoing discussion, it is apparent that the design of a mechatronic system may well require the use of a number of overlapping descriptive and other 'models' in order to provide an effective basis for the design process. In order to be effective, the role of any individual model in describing a particular feature or features of the system must be properly understood together with its relationship with other model formats. Once this understanding has been obtained an appropriate model may then be chosen by the designer to emphasise desired features in the design linking this to the strategy to be used in the design process.

Models of various types play a major and important role in the design process. At one level, they provide a means of communication of matters such as function and purpose, something which is of particular importance when considering the multi-disciplinary nature of mechatronics, while at another they enable system properties and performance to be evaluated. Faced with the demands of industry to reduce development time scales for products of increasing technological complexity while meeting customer demands in areas such as quality and reliability, design models are likely to play an increasingly important role. Indeed, it is possible that the effectiveness of concurrent engineering may well ultimately depend upon the ability to develop effective means of modelling, or of 'rapid prototyping', in a particular design environment.

Mechatronics, by virtue of the need to integrate a range of technologies, and hence to define the interaction between those technologies, presents particular problems for the development of effective design models. In considering the requirements for the modelling of a mechatronic system it is therefore useful to begin by examining the characteristics of the primary areas of engineering and technology involved in the mechatronics design process and their associated solution domains. Taking a much simplified approach to these solution domains it can be argued that:

- The design of the mechanical elements of the system is primarily concerned with spatial relationships and interactions.
- The design of the electronic component of the system is primarily concerned with signal processing and the interconnection of discrete components and devices.
- The design and engineering of the associated software is primarily concerned with the development of data and information processing algorithms.

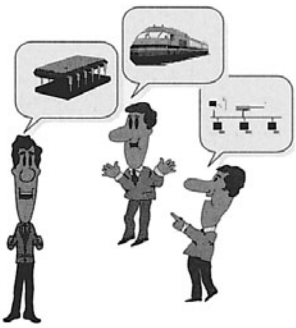

Figure 1.23 Communications problems.

A particular problem highlighted by the above is the difficulty of ensuring appropriate communication between the individual specialists involved in the design of any mechatronic system since, as illustrated by Fig. 1.23, each will tend to think of the problem in terms of their own area of specialism. The role of the mechatronic engineer is often therefore to act as the link between the specialists and to provide the necessary channel of communication through which ideas and thoughts can be transferred.

Model formats

There are available a number of different model formats that may be used in support of the design of a mechatronic system. These are described in the following sections.