Peter Hehenberger · David Bradley
Editors

Mechatronic Futures

Challenges and Solutions for Mechatronic Systems and their Designers

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Foreword

It is an honour and a pleasure to write a foreword for the Mechatronic Futures book cleverly devised and edited by Prof. David Bradley and Dr. Peter Hehenberger. This contribution is written on behalf of numerous colleagues in the UK and the wider world who have supported the Mechatronics Forum in its mission and activities. Founded in 1990, this forum was formed as an interest group in the UK and is currently sponsored by and part of the Institution of Mechanical Engineers (IMechE), London. Over the years since its formation, it has enabled professional engineers from industry and academia to share innovative ideas in this field and has acted as body to champion the discipline.

Mechatronics is a domain which spans most of my professional career and has been at the centre of fascinating technological developments and trends in the modern world. *Mechatronic Futures* reviews the origins of the discipline, explains the technological changes that have emerged and explores how mechatronics will further develop in future years, the challenges it will face and how it might need to respond in helping to address some of the grand challenges that are facing mankind.

The concept of mechatronic systems was first used in Japan in the 1960s by Tetsuro Mori to reflect the emerging role of electronic components used in the control and operation of what had previously been inherently mechanical systems. The Mechatronics Forum came into existence at a meeting held at IMechE's London headquarters on 30 October 1990, attended by over seventy engineers excited by an interest in the emerging discipline. It was the first organisation in the Western World that recognised the importance of mechatronics and began to promote it. Although the word mechatronics has been around since the late 1960s, it was only in the early 1990s that it was used to any great extent in the UK. However, during the 1990s, with the activities of the Mechatronics Forum, the term mechatronics and the engineering discipline that it encompasses became widely recognised.

Mechatronics today extends beyond the integration of mechanical, electronic and computer engineering. Many engineers now see it as embracing a wider range of engineering activities, from design through manufacture to the market place.

Hence, they regard mechatronics as a major influence in pulling together and integrating the many aspects of engineering which increased specialisation has tended to push apart from each other during the past decades. It was in an attempt to solve this increasingly challenging problem that the Mechatronics Forum was conceived as a first step towards the building of bridges between the many technologies, philosophies and disciplines which comprise mechatronics and the professional institutions that are committed to their own particular specialised subjects. In the UK, engineering institutions are important in sharing technical subjects between professionals in industry and academia. They accredit undergraduate and postgraduate courses as suitable for covering the academic components of a chartered engineer's development, and they grant Chartered status to those whose careers show sufficient engineering responsibility and understanding to be leaders in their field.

The Mechatronics Forum for its first ten years was supported under an inter-institutional arrangements, with secretarial and administrative services provided alternately by the Institution of Mechanical Engineers (IMechE) and the Institution of Engineering and Technology (lET). Following this, the Forum has been supported by the IMechE and linked with the Mechatronics, Informatics and Control Group (MICG).

The founding Committee of the Mechatronics Forum was charged with a broad remit including setting up and establishing a publication of a newsletter, popularising mechatronics, focusing on educational issues and seeking ways of bringing together all those interested in mechatronics, and especially of promoting closer links between industry and academia. Many of these are still the remit of the Forum today, and significant advances in a number of areas have been facilitated through the auspices of the Forum. The Mechatronics Forum Committee has included a number of members from outside the UK, to help with the internationalisation of the Forum and its activities as illustrated by most of the biennial international conferences being hosted outside the UK.

The original founding members of the Forum were Prof. Jack Dinsdale, the first chair of the organisation, Prof. Jim Hewit and Prof. David Bradley, each of whom were made Honorary Life Presidents of the organisation.

The showcase activity of the Mechatronics Forum since its formation has been the series of biennial international conferences, the first and longest standing conference on mechatronics in the world, featuring important contributions from around the globe. The very first conference was organised by Prof. David Bradley, whilst working at Lancaster University. The conferences have been an excellent means of sharing mechatronic ideas, thinking and applications more widely.

Hosts and venues for the fifteen conferences were:

1989: Lancaster University, UK
1990: Cambridge University, UK
1992: University of Dundee, Scotland, UK
1994: Technical University of Budapest, Hungary
1996: University of Minho, Portugal
1998: University of Skövde, Sweden

2000: Georgia Institute of Technology, Atlanta, USA
2002: University of Twente, The Netherlands
2004: Middle East Technical University, Ankara, Turkey
2006: Penn State University, Great Valley, Pennsylvania, USA
2008: University of Limerick, Ireland
2010: ETH, Zurich, Switzerland
2012: Johannes Kepler University, Linz, Austria
2014: University of Karlstad, Sweden
2016: Loughborough University, UK

Another highlight in the calendar of the Mechatronics Forum is the Prestige Lecture. Every year, an eminent speaker is invited to the headquarters of IMechE to deliver a topical and sometimes challenging lecture to the members. The following are some of the Prestige Lecturers to date:

- *The Role of Xero-Mechatronics in New Product Development*, Dr. John F. Elter, Xerox Corporation, April 1995
- *Advances in Mechatronics: the Finnish Perspective*, Vesa Salminan, FIMET, Finland, May 1996
- *The Industrial Benefits of Mechatronics: the Dutch Experience*, Prof. Job van Amerongen, University of Twente, the Netherlands, May 1997
- *Virtual Worlds—Real Applications: Industrial and Commercial Developments in the UK*, Prof. Bob Stone, University of Birmingham, May 1998
- *Mechatronics Solutions for Industry*, Prof. Rolf Isserman, University of Darmstadt, April 2000
- *Intelligent Mechatronics: Where to go*? Prof. Toshio Fukuda of Nayaga University, July 2001
- *Bionics: New Human Engineered Therapeutic Approaches to Disorders of the Nervous System*, Prof. Richard Norman, University of Utah, July 2003
- *GM's Approach to Eliminating Complexity and Making the Business More Successful*, Dr. Jeffrey D. Tew, General Motor's R&D Center, September 2004
- *Mechatronic Design Challenges in Space Robotics*, Dr. Cock Heemskerk and Dr. Marcel Ellenbroek, Dutch Space, June 2005
- *Cyborg Intelligence: Linking Human and Machine Brains*, Prof. Kevin Warwick, University of Reading, May 2006
- *Iterative Learning Control—From Hilbert Space to Robotics to Healthcare Engineering*, Prof. Eric Rogers, University of Southampton, March 2007
- *World Water Speed Record Challenge—The Quicksilver Project*, Nigel McKnight, Team Leader and Driver, Quicksilver (WSR) Ltd., May 2008
- *Meeting the Challenges and Opportunities of Sustainability through Mechatronics Product Developm*ent, Prof. Tim McAloone, Technical University of Denmark, Denmark, May 2009
- *I'm a Control Engineer: Ask me what I do*? Prof. Ian Postlewaithe, University of Northumbria, March 2010

- *Sports Technology: The Role Of Engineering In Advancing Sport*, Dr. Andy Harland, Sports Technology, Loughborough University, September 2011
- *Modelling, Control and Optimisation of Hybrid Vehicles*, Lino Guzzella, Swiss Federal Institute of Engineering, October 2013
- *The Past, Present and Future of Mechatronics: A Personal Perspective*, Professor Emeritus David Bradley, Abertay University, February 2015.

In addition to the biennial international conference series and the Prestige Lectures, the Forum has supported and facilitated many other activities related to mechatronics and its wider promotion including:

- Technical visits to industrial and academic organisations where these are open to members.
- Technical seminars and workshops focussed on particular aspects of the discipline.
- Mechatronics Student of the Year Award, a competition open to final-year degree students and master's level students based upon their final project dissertation.

To conclude the Mechatronics Forum is part of the Mechatronics, Informatics and Control Group of the Institution of Mechanical Engineers. It has had an important role in popularising mechatronics in the UK and, beyond, focusing on educational issues and promoting linkages between industry and academia, and seeking ways of bringing together all those interested in mechatronics.

Over the past twenty-five years or so, this has been encouraged through a variety of conferences, lectures, seminars, events and visits to industry and research centres. Mechatronics today is significant in industries worldwide. In our global environment, collaboration across the world is valuable in moving towards sustainable systems and solutions to societal challenges. The biennial conferences in particular have proven to be very fruitful in sharing ideas and stimulating debate between those at the forefront of mechatronics development which we hope will benefit societies across the world. Mechatronic future sets out a vision and narrative of how some of the future societal challenges might be addressed and the role mechatronics has to contribute to this.

Prof. Philip Moore
Falmouth University

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Editors and Contributors

About the Editors

Peter Hehenberger is an assistant professor and deputy head at the Institute of Mechatronic Design and Production at the Johannes Kepler University of Linz (JKU) in Austria. He received his diploma degree and his doctorate degree in Mechatronics from JKU in 2000 and 2004, respectively.

His core competencies cover model-based mechatronic system design and include mechatronic design, systems engineering, design processes and model-based design methods. He has published over 70 peer-reviewed papers in international journals and conference proceedings and been guest editor for two journals' special issues. In addition, he has authored and co-authored 3 books related to the field.

He is presently a member of the Scientific Network of Linz Center of Mechatronics (LCM), Austria, and leads several international research projects related to the research area "*Process Modelling and Mechatronic Design*" at the LCM.

Peter Hehenberger is also one of the initiators of SmaPro,[1] a qualification network for the future challenges of Industry 4.0 together with 13 partners—four academic partners, four small and mid-sized companies as well as five large companies.

He lectures on the topics in product development, model-based systems engineering, mechanical engineering, mechatronic design, computer-aided design, simulation and manufacturing. He is currently co-supervising 6 doctoral students and 5 master theses by research students.

Among other scientific service activities, Peter Hehenberger organised the International Workshop Series on Mechatronic Design (Linz 2012, Paris 2013, Leuven 2014). He is also member of VDI, ASME, IFIP WG5.1 ("*Global Product development for the whole life-cycle*") and Design Society, where he co-chairs a Special Interest Group (SIG) on Methodologies for Design, Integration, Modelling and Simulation of Cyber Physical Systems.

[1]Smart Production: Machine data analysis and interpretation in production.

Between February and April 2015, he was an invited visiting professor at the Universite de Technologie de Compiegne, Departement Genie des Systemes Mecaniques, France.

David Bradley is currently professor emeritus at Abertay University. He began his academic career when he joined Lancaster University in 1972 and has been engaged with and involved in aspects of mechatronics since the mid-1980s and was responsible, with Prof. Jim Hewitt and Prof. Jack Dinsdale, for the establishment of the UK Mechatronics Forum, now the Mechatronics Forum.

In the course of a period of some 30 years at Lancaster University, the University of Wales Bangor and Abertay University, he has been involved in various aspects of the design, manufacture and operation of mechatronic systems for applications ranging from intelligent robots to medical and telecare systems and design methods. This included the establishment at Lancaster University in the late 1980s of some of the first mechatronics degree programmes, at both undergraduate and master's levels, in the UK as well the EPSRC-funded Engineering Design Centre which had mechatronics as a focus.

Most recently, he has been interested in exploring the interaction between mechatronics, the Internet of Things and Cyber-Physical Systems, and in particular how the design process can be adapted at both the systems and component levels to accommodate context-dependent systems elements derived from cloud-based technologies. This includes the means by which the design process enables the development of participatory systems structured around user need, essentially placing the user, who may be interested only in context, at the heart of the process of system integration, and including issues related to user privacy and security. He is also working in an advisory or consultative capacity with research groups in the UK and elsewhere on projects to develop advanced prostheses and evaluate mechatronics design methods.

A fellow of the Institution of Engineering and Technology (IET), David is the author, co-author or contributing editor for 7 textbooks, including 3 on mechatronics, some 50 journal papers and book chapters along with over 120 conference papers. He has also been responsible for the development of, and teaching on, mechatronics courses in the UK since the mid-1980s and has lectured on and acted as consultant for similar courses in, among others, the USA, Singapore, South Africa, Indonesia and Colombia.

Contributors

Nicolas Albarello is a researcher in the Systems Engineering Department of Airbus Group Innovations. He received his Ph.D. in Sciences for the Engineer from Ecole Centrale Paris in France. Since 2012, he has been contributing to several research projects in the field of systems engineering but also to operational projects for civil aircrafts and space systems. His main research topics include optimisation of systems (architecture, sizing, control), modelling and simulation, and decision aid in design.

Alexandre Arnold is a research engineer at Airbus Group Innovations in the Model-based System and Software Engineering team. He graduated in 2010 with a double diploma in engineering from the Ecole Centrale Lyon in France and the Technical University Munich in Germany, specialising in aeronautics and aerospace. He has since been working on various research projects, as well as operational projects for civil/military aircrafts and space division. The research topics have mainly been focused on MBSE, modelling and simulation, formal verification and systems of systems.

Jorge Azorín-López received a degree in Computer Engineering in 2001 and a Ph.D. degree in Computer Science at the University of Alicante (Spain) in 2007. Since 2001, he has been a faculty member of the Department of Computer Technology at the same university, where he is currently an associate professor and the deputy director of Research.

He was awarded the Post-doctoral Research Fellowship "*Automatic visual inspection of shape defects on specular surfaces. Methods to compensate low sensitivity of 3D image acquisition and reconstruction techniques*" by the Spanish Ministry of Science and Education for research at University of Edinburgh.

He has worked in 16 research projects and has published more than 50 papers on computer vision and computer architecture in several journals, conferences and book chapters. He has also served as a reviewer to numerous scientific journals and international conferences. Currently, he is associate editor of the IJCVIP journal. Current research interests include human behaviour analysis using computer vision, visual inspection and 3D modelling and analysis using computer vision.

Stefan Boschert graduated in physics from the University of Freiburg. After gaining his Ph.D. in 2000, he worked for an engineering company in Basel, Switzerland, on mechanical and hydro-dynamical modelling and simulation. Since 2004, he has worked at Siemens Corporate Technology in Munich, Germany, in the technology field of automation and control.

As a Senior Key Expert Engineer he is responsible for simulation-based system development, which includes multiphysics simulation, process models and integrated data and simulation model-based approaches. He has expertise in the set-up and implementation of mechatronic design processes and their extension to cyber-physical systems. Further, he was the manager of the department's contribution to several national and international publicly funded projects.

Jordan H. Boyle is a lecturer in the School of Mechanical Engineering, at the University of Leeds, and is also a founding member of the EPSRC National Facility for Innovative Robotic Systems, an advanced manufacturing facility. He obtained his B.Sc. and M.Sc. degrees in Electrical Engineering from the University of Cape Town, South Africa, before moving to the University of Leeds for a Ph.D. in Computational Neuroscience in the School of Computing.

Jordan's research lies on the interface of engineering and biology, and his main interest is in using biological inspiration to develop locomotion and navigation strategies for mobile intelligent robots. Since the phenomenal complexity of biological systems makes it extremely challenging to decipher the mechanisms involved—a crucial first step in the biologically inspired design process—Jordan prefers to focus on relatively simple invertebrate systems. To date, his specific research projects have included developing a miniature mobile robot for use in colonoscopy and a snake-like robot controlled by a model of the C. elegans nervous system.

Robotics applications underlie Jordan's interest in advanced manufacturing. Indeed, one of the major barriers to the wider uptake of mobile autonomous robots is cost. If robots could be made cheaply and in large volumes, they would be deployed more widely, more frequently and in greater numbers.

Matthieu Bricogne is an assistant professor at the Mechanical Systems Engineering Department/Roberval Laboratory (UMR 7337) in Université de Technologie de Compiègne (UTC). He obtained his M.Sc. in Mechanical Engineering and a Mechanical Engineering Degree at UTC in 2004.

He has worked for 5 years for Dassault Systèmes, an industrially leading company specialising in 3D and Product Lifecycle Management (PLM) software. He obtained his Ph.D. degree in Mechanical Engineering from the Ecole de Technologie Supérieure in Montréal (ETS) and UTC in 2015. His main research topics are collaborative design, mechatronics system design and knowledge-based engineering within a PLM environment.

Since 2013, he has been vice-director of the ANR LabCom DIMEXP (DIgital MockUp multi-EXPertises) joint laboratory UTC/DeltaCAD, whose main objective is to develop methods and models to improve the integration of multidisciplinary expertises and heterogeneous data in advanced digital environments.

Marc Budinger is an alumni of the ENS Cachan (Paris) in Applied Physics, has a Ph.D. in Electrical Engineering (2003) and a HdR (habilitation) in mechanical engineering (2014) from Toulouse University.

Marc is an associate professor in the Mechanical Engineering Department of INSA Toulouse. His current research topic in the ICA laboratory concerns the model-based design of electromechanical and piezoelectric actuators and actuation systems. He is currently investigating the conjoint use of estimation/prediction models, 0D/1D simulation models, reliability models and metamodels from 3D FEM simulation for design and optimisation of mechatronics systems.

Benoît Eynard is currently the director of the Institute for Mechatronics at the Université de Technologie de Compiègne—UTC, France. In 2007 he joined UTC as a full professor, leading the Department of Mechanical Systems Engineering until 2012. He is also member of the UMR CNRS/UTC 7337 Roberval. Previously, he was an assistant professor at the Université de Technologie de Troyes where he managed the M.Sc. programme in Information Technology for Mechanical Engineering.

Since 2013, he has been general chairman of the academic group of French Society of Mechanical Engineering (AFM) dealing with factories of the future: integrated design and advanced manufacturing also known as AIP-PRIMECA network.

He is also a member of the IFIP Working Group 5.1 "*Global Product development for the whole life-cycle*" and of the Design Society where he currently leads the Special Interest Group on "*Design Methods for Cyber-Physical Systems*".

In 1999, he obtained a Ph.D. in Computer-Integrated Manufacturing from the University of Bordeaux. Now, he is a recognised researcher in product lifecycle management, collaborative design, systems engineering, mechatronic design, digital factory, manufacturing process management, eco-design and sustainable manufacturing. He has published over 50 papers in international journals and 150 international conferences. He also has been guest editor for 10 journal special issues and academic books.

Nicholas Fry is undertaking a Ph.D. research degree within the Leeds EPSRC National Facility for Innovative Robotic Systems, UK. He received his B.Eng. and M.Eng. degrees in Mechatronics and Robotics from the University of Leeds. Nicholas is researching advanced manufacturing techniques and has recently developed a novel 3D printing process, using industrial robotic arms, with the aim of autonomously embedding mechatronic components within rapidly fabricated structures.

Andres Fuster-Guillo received the B.S. degree in Computer Science Engineering from Polytechnic University of Valencia (Spain) in 1995 and the Ph.D. degree in Computer Science at the University of Alicante (Spain) in 2003.

Since 1997, he has been a member of the faculty of the Department of Computer Technology at the University of Alicante, where he is currently a professor. He has worked in more than 15 research projects and has published more than 40 papers on computer vision and computer architecture.

His current areas of research interest include vision systems to perceive under adverse conditions, 3D vision systems, automated visual inspection and artificial neural networks.

He was deputy coordinator of the Polytechnic School at the University of Alicante for seven years. Currently, he is director of the Secretariat for Information Technology at the University of Alicante, where he has coordinated and participated in several strategic technology projects: Open University (transparency portal and open data), UACloud, and Smart University, among others.

Thomas J. Howard is an associate professor at the Technical University of Denmark (DTU) after gaining his Ph.D. in Engineering Design from the University of Bath, UK. His main field of expertise is in robust design and more broadly engineering design research. He currently heads the robust design group at DTU and is the current chairman of the Design Society's Special Interest Group on Robust Design.

Tom has numerous past and present Ph.D. students and has attracted large amounts of research funding from both public and private sources including investment for the Novo Nordisk-DTU Robust Design Programme of around €1.5M. He sits as an elected member of the Design Society's advisory board and has received several accolades such as the DTU Innovation Prize 2014 and the BMW European Scientific Award. He has also published work in many top engineering design journals.

In addition to the research on robust design, Tom has a keen interest in innovation and technical entrepreneurship. He has been a keynote speaker at the European Innovation Academy several times and has been responsible and instrumental in numerous spinout companies.

Simeon Keates is professor and deputy pro-vice-chancellor of the Faculty of Engineering and Science at the University of Greenwich. He was formerly chair of HCI and head of School of Engineering, Computing and Applied Mathematics at Abertay University in Dundee and associate professor at the IT University of Copenhagen, where he lectured in the design and digital communication study line. He obtained his Ph.D. from the University of Cambridge, where he also worked as an Industrial Research Fellow in the Engineering Design Centre.

After leaving Cambridge, he moved to the USA and joined the Accessibility Research Group at the IBM TJ Watson Research Center before moving to Boston and working at ITA Software (now part of Google) as a usability lead designing interfaces for Air Canada. Simeon also has an extensive history of consultancy, with clients including the Post Office (Royal Mail), the US Social Security Administration, the UK Department of Trade and Industry, Danish Broadcasting Corporation (DR) and Lockheed Martin.

Antonio Lanzotti is the founding director of the Fraunhofer IDEAS (Interactive DEsign And SimulaTION) LABORATORY (www.ideas.unina.it) and is leading a research group on design methods at the University of Naples Federico II. He received his master's degree in Mechanical Engineering (summa cum laude) from Università degli Studi di Napoli Federico II in 1985.

From 1986 to 1987 he worked for the IT Department of Aeritalia. In 1990 he received a Ph.D. in Material and Production Technology from the University of Naples Federico II.

From 1992 to 1997, he undertook teaching and research activities at the Department of Aerospace Engineering as researcher and then from 1997 in a teaching position as associate professor. In 2001 he was appointed Full Professor in Design Methods of Industrial Engineering at University of Naples Federico II. He now teaches "*Product Design and Development*" and "*Engineering drawing*". He has been the only teacher of "*Statistics for Innovation*" not belonging to the "*Experimental Statistics for Engineering and Technology*" Scientific Sector.

He is associate editor in chief of the International Journal on Interactive Design and Manufacturing published by Springer. He is a reviewer for international journals, and he has been invited to lecture in international conferences and has promoted and organised many international conferences as a member of Steering and Scientific Committees. He was the President of the Italian Association of Product Design from 2004 to 2011. Further, he is the past president of the Italian Scientific Sector on Design Methods for Industrial Engineering (SSD ING-IND/15). Finally, he is responsible for the international agreement between the University of Naples Federico II and TU Chemnitz, ESTIA of Biarritz and University of Bartin, Turkey.

Julien Le Duigou is an associate professor at the Department of Mechanical Systems Engineering of Université de Technologie de Compiègne and researcher at Roberval Mechanical Laboratory (UMR CNRS 7337) and Labex MS2T "*Control of Technological Systems-of-Systems*" research centres. He obtained his mechanical engineering degree and his M.Sc. in Mechatronics in 2006 from Supmeca engineering school and University of Toulon, respectively, and a Ph.D. in Mechanical Engineering in 2010 from Ecole Centrale engineering school.

He is also member of the IFIP working group 5.1 dealing with "*Global Product development for the whole life-cycle*" and of the IEEE Systems Man and Cybernetics Society. Currently, his research interests include product lifecycle management, knowledge management, interoperability and product/process integration. He published more than 50 papers in refereed international journals, books and conferences.

Craig Melville is a Ph.D. student studying in the Space Mechatronic Systems Technology Laboratory (SMeSTech) at the University of Strathclyde in Glasgow, having received his M.Eng. in Product Design Engineering in 2013 from the university's Department of Design, Manufacturing and Engineering Management (DMEM). His terrestrial design projects have involved a range of intra-discipline skills such as computer-aided design and simulation, structural analysis and design optimisation.

The projects he has been involved in allowed him to work with both Scottish SMEs and large international organisations; one project for Jaguar Land Rover allowed them to make design changes capable of saving up to £1,000,000 in assembly and manufacturing costs over 3 years.

Craig is currently focused on work relating to spacecraft and space robotic design for his Ph.D. studies, which he is due to finish in 2017. His work in the area focuses on the development of a design methodology for flexible use within space and complex design organisations. Other interesting realms of work include the design and optimisation of a multifunctional spacecraft interface, the development of universal interface design principles and the role of virtual reality and video games in conceptual/low TRL design phases.

Christopher Milne is associate chief information officer (Information Assurance and Governance) at the University of St. Andrews.

He gained a B.A. (Hons) in Librarianship and Information Studies at the Robert Gordon University (RGU) in 1994 before obtaining a PgDip in Information Analysis (1995). Following a spell as an IT trainer, Chris returned to RGU, where he was responsible for developing IT skills teaching in undergraduate and postgraduate modules.

In 1998, Chris joined the then University of Abertay Dundee, where he had a rich and varied career, predominately in the field of information management (academic librarian) and latterly as the officer responsible for corporate information and risk management across the university, as a Deputy Head of Information Services. Whilst at Abertay he read for a Masters in Records Management at Northumbria University (2007). He has published in the fields of information literacy—integrating core skills into the curriculum (2004), and records management—advocating the use of records management information retrieval philosophies as a means of improving access to information from corporate Websites (2007) and (2010).

In his current role at the University of St. Andrews, he is responsible for information governance and records management across the institution. He has a business focused view of legislation and regulation—in that it should aid institutions in their mission and development and not hinder them via obsessive compliance and the introduction of unnecessary and/or artificial barriers. As part of the senior management team of the University's IT Services, he is also responsible for providing leadership and direction as IT Services emerges from a period of reorganisation. From 2015, he also gained responsibility for the day-to-day management of the university's complaint management function, developing organisational learning by assessing complaint contributory factors.

Aiguo Ming received the M.S. degree in Precision Engineering from Yamanashi University, Japan, in 1987, and the Ph.D. degree in Precision Machinery Engineering from the University of Tokyo, Japan, in 1990.

He is currently a professor in the Department of Mechanical Engineering and Intelligent Systems, The University of Electro-Communications, Tokyo, Japan. His current research interests include biomimetic hyper-dynamic robotics, biomimetic soft robotics, high-speed robotic hand systems with high-speed sensors, application of mobile manipulator systems and precise measuring mechatronic systems.

Philip Moore became pro-vice-chancellor (R&I) at Falmouth University in 2012. He leads all research and development, and is also chair of the Centre for Smart Design. Philip has been a visiting professor at University of Skövde, Sweden, since 1994 and on the Board of Directors of the Smart Home and Building Association (SH&BA). Phil was previously director of Research at De Montfort University (DMU) and director of the Mechatronics Research Centre and architect of the Intelligent Machines and Automation Systems (IMAS) laboratory. Phil studied Production Engineering and Management at Loughborough University whilst working in the automotive industry. He then studied for a Ph.D. in Robotics, whilst working in research at Loughborough, before joining as an academic member of staff, where he was a founder member of the Manufacturing Systems Integration (MSI) Research Institute.

Phil's own research focuses on smart digital technologies and their integration with sustainable design to address some of the societal grand challenges such as climate change, energy resilience, health and well-being and the ageing society. Other research interests include digital manufacturing and automation.

Phil was responsible for the founding of Digital Games at Falmouth and the associated research in computer games technology and was the architect of the successful European Research Area (ERA) Chair bid for €2.4 million to the FP7 programme in Digital Games research. Phil has supervised some 40 Ph.D. programmes to completion and has been external examiner on nearly 50 occasions.

Philip has won research funding from UK and EU agencies—EPSRC, ESRC, InnovateUK, EU FP, British Council, The Royal Society, RDA's and Industry. He has established a network of research collaborators in industry and academia in UK, Sweden, Germany and Italy.

Phil is vice-chair of Mechatronics, Informatics and Control Group, IMECHE, and chair of the Mechatronics Forum.

Stanislao Patalano is an associate professor in Design and Methods of Engineering Design at Department of Industrial Engineering, University of Naples Federico II.

He gained a master's degree in Mechanical Engineering in 1997, Ph.D. title in "*Machine Design and Construction*" in 2001, at the University of Naples Federico II. From 1999 until 2010, he was researcher in the Scientific Area of Design and Methods of Engineering Design. In 2006, he was visiting professor at the Institut Supérieur de Mécanique de Paris—SUPMECA, France, working on tolerance design.

He has published more than 90 papers in International Conference Proceedings, International Journals and National Journals. His research interests include CAD methodologies and knowledge-based engineering, variational analysis, tolerance design and design for assembly, and mechatronic systems design.

He has been member and coordinator of research groups within research projects funded by national public agencies (MIUR, Campania Region). From 2011 to 2014, he has been scientific responsible for the research activities of the Department of Industrial Engineering within "*PON Project 01_01268: Digital Pattern Development: a pattern driven approach for industrial product design, simulation and manufacturing*", in cooperation with FIAT Item, Fiat Chrysler Automobiles (FCA), Ansaldo-Breda, Ansaldo STS, SMEs (Technodesign, Tecnosistem, STEP Sud Mare).

He has scientific responsible for the COGITO (COmputer GeometrIc Modelling and SimulaTiOn) Laboratory at the Department of Industrial Engineering of the University of Naples Federico II. COGITO Laboratory is a part of IDEAS (Interactive DEsign And Simulation) Laboratory, established between University Federico II and Fraunhofer IWU.

He is currently professor of Geometric Modelling and Virtual Prototyping and Engineering Drawing at the University of Naples Federico II.

From 2012 to present, Promoter and Responsible for the University of Naples Federico II of the Academic Course aimed to a double master's degree: "*Master Degree in Mechanical Engineering for Designing and Manufacturing*" and "*Diplôme d'Ingénieur Supméca*".

Rob Richardson is professor of Robotics at the School of Mechanical Engineering, University of Leeds, UK, and a fellow of the IMechE. He is director of the Leeds EPSRC National Facility for Innovative Robotic Systems, a world class, facility for designing and creating robotic systems initiated in August 2013. He is also director of the Institute of Design, Robotics and Optimisation at the School of Mechanical Engineering. He is co-director of the UK EPSRC cities grand challenge, awarded in November 2015 with the aim of using robotics to perform minimally invasive infrastructure repair.

He held a prestigious research contract to explore the Great Pyramid of Giza, Egypt, using robotic technology and has discovered writing in the Great Pyramid that was hidden for thousands of years.

His current research interests focus around the fabrication of complex robotic systems with application to exploration robotics for safety and security including: inspection and repair of city infrastructure; protecting life by accessing confined spaces to find survivors of natural disasters; gathering information on terrorist and military threats; inspecting inaccessible industrial plants; or processes utilising enhanced sensing and networking.

Roland Rosen studied mathematics with a minor in economics at the Technical University of Munich. After joining Siemens in 1989, he worked in different positions in the area of modelling, simulation and optimisation of technical systems, plants and infrastructure solutions. Currently, he is at Siemens Corporate Technology as a Principal Key Expert Research Scientist responsible for the international focus area of modelling and simulation.

He is involved in different activities related to “Industrie 4.0”, and he is a member of expert committees of VDI/VDE Society for Measurement and Automatic Control (GMA). Roland Rosen works on the realisation of simulation-based methods for mechatronic systems and complex plants. His specific interest is in the seamless integration of simulation into all lifecycle phases of system development and the use and reuse of simulation models and technologies during operation and services.

David Russell was awarded his Ph.D. in recognition of his research at the UK Atomic Energy, the University of Manchester and the then Liverpool Polytechnic. His thesis included the design of an intelligent controller for a novel fast reactor using a fluidic control schema.

Dr. Russell is a professor of engineering at Penn State Great Valley where has spent the last 30 years. Dr. Russell was past chair of the campus IT Advisory Board and was a founder member of the University Committee for Enterprise Integration, which is part of the SAP University Alliance programme. Whilst senior division head for fourteen years, Professor Russell designed and implemented two professional postgraduate degrees in Software Engineering and Systems Engineering which are now available on-campus and online.

He has taught at the undergraduate and post graduate level in the UK, USA and Asia over the past half-century and has created, managed and taught systems engineering, information technology and computer engineering activities including scholarly and professional international conferences. He has delivered invited and plenary lectures in over thirty countries. Dr. Russell serves the editor for the Americas for the International Journal of Advanced Manufacturing Technology, a Springer publication.

Dr. Russell is a past fellow of the Institute of Electrical Engineering and fellow of the BCS (British Computer Society) and a current fellow of the Institute of Mechanical Engineers (IMechE) and a Chartered Engineer.

Prior to Penn State Dr. Russell held several positions as a technical executive with factory systems integration companies in the USA and the UK and has held several faculty appointments in other universities. He is the author over 120 technical papers and an active international member of the Mechatronics Forum, an IMechE scholarly society.

Marcelo Saval-Calvo received the degree in Computer Engineering in 2010 and the M.Sc. in 2011 from the University of Alicante (Spain) with a master's thesis in the area of computer vision. He received his Ph.D. in 2015 from the University of Alicante focused on 3D registration of rigid and deformable subjects.

He is currently working in the Computer Technology Department at the same university. He was awarded a research fellowship by Regional Ministry of Education, Culture and Sports of Valencian Government for researching at the University of Edinburgh. His current research interests include human behaviour analysis using computer vision, 3D registration of rigid and deformable data.

Maarten Steinbuch is distinguished university professor at Eindhoven University of Technology. He received the M.Sc. degree and Ph.D. degree from Delft University of Technology, in 1984 and 1989, respectively. From 1987 to 1998, he was with Philips Research Laboratories in Eindhoven as a Member of the Scientific Staff. From 1998 to 1999 he was manager of the Dynamics and Control Group at Philips Center for Manufacturing Technology.

Since 1999, he has been full professor and chair of the Control Systems Technology Group of the Mechanical Engineering Department of Eindhoven University of Technology.

He has been editor in chief of IFAC Mechatronics (2009–2015), scientific director of the Research Centre High Tech Systems of the Federation of Dutch Technical Universities, director of the TU/e Graduate Program Automotive Systems, initiator of the TU/e Bachelor Automotive, member of the board of AutomotiveNL, member of the Formule E team, member of the advisory board of the High Tech Institute and of Nobleo Technology BV, co-founder of MI-Partners BV, co-founder of Mechatronics Academy BV, co-founder of Preceyes BV and founder of Steinbuch in Motion BV. He is CEO of Medical Robotics Technology BV.

Since 2014, he is also the scientific director of the new TU/e High Tech Systems Center HTSC. In 2003, 2005, 2008 and 2015, he obtained the "Best-Teacher" award of the Department of Mechanical Engineering, TU/e. In 2008 as well as in 2014, his research group obtained the QANU excellence rating [5555]. In 2013 he was appointed distinguished university professor at TU/e. In 2015 Maarten received the KIVI Academic Society Award. His research interests are modelling, design and control of motion systems, robotics, automotive powertrains and of fusion plasmas.

Jonas Mørkeberg Torry-Smith has been involved in design of mechatronic systems for more than a decade performing research within the field as well as carrying out mechatronic product development in industry.

He holds a Ph.D. in systematic design of mechatronic products. The research has been aimed at procedures for mechatronic development integrating the mechanical, the electronics and the software engineering discipline. The research also comprises proposals for methods for modelling mechatronic concepts across the disciplines elucidating central conceptual dependencies.

From 2002 to 2014 Jonas Torry-Smith was affiliated to IPU—a consulting company—working with mechanical and mechatronic development as a consultant for Danish and international companies. The range of projects comprises innovation projects, concept scouting as well as total turn-key projects. The projects have been carried out as project manager, team member or as specialist. In addition, on-the-job training has been performed for international companies based in Denmark. He has recently switched to the Pharma industry working for a large international med-tech company.

Steve Watt is chief information officer at the University of St. Andrews. A native of Scotland he was born in Dundee in 1971 and currently lives north of Dundee in the county of Angus.

Steve was educated at the then University of Abertay Dundee where he gained a Bachelor of Science degree in Building Engineering and Management, a Master of Science degree in Information Technology and later a Master of Business Administration degree.

Steve is a European engineer, chartered engineer, chartered IT professional and a fellow of the British Computer Society and has 20 years' experience working within the information technology field.

He has worked primarily in the Higher Education sector in a variety of roles which have included Network Analyst, IT Manager, Deputy Head of Information Services and Chief Information Officer (CIO).

Steve has also worked in the private sector for Low & Bonar plc in both Europe and North America. In this role, he was responsible for the coordination and delivery of corporate IT provision at around 52 locations which included the provisioning and management of wide area networking, telecommunications, groupware and systems management working with outsourced partners centralising the core ICT support for all sites to the UK. He has also worked as a consultant across a range of industries.

In his current role as CIO at the University of St. Andrews, he is responsible for the IT services and change management functions comprising of around 90 staff and is a member of the University Senior Management Team. He is responsible for the strategic development of all IT provision, information assurance and governance and business transformation activities.

He is a member of the Board of Management of Dundee and Angus College, chair of the Higher Education IT Directors in Scotland Group and a member of the Scottish Government Technical and Design Board. Steve is a frequent contributor at IT conferences including as conference chair and panellist.

George R. S. Weir is a lecturer in Computer and Information Sciences at the University of Strathclyde in Glasgow, Scotland. He holds academic qualifications from three Scottish universities, including a Ph.D. from the University of Edinburgh. In addition to teaching and research supervision, he has published extensively in the areas of cybercrime, security, readability and corpus linguistics.

He is a member of the BCS Forensics and Cybercrime Specialist Group, the Association of Computing Machinery, the British Computer Society and the Higher Education Academy. He is also a senior member of the IEEE and a fellow of the Winston Churchill Memorial Trust and a fellow of the Royal Society of Arts.

Xiu-Tian Yan is professor in Mechatronic Systems Technology, the director of the Space Mechatronic Systems Technology Laboratory (SMeSTech) and deputy director of Strathclyde Space Institute, based in the Department of Design, Manufacture and Engineering Management (DMEM) of the University of Strathclyde. He is the vice-chairman of the Mechatronics Forum in the UK and chairman of the Robotics and Mechatronics Technical Professional Network of the Institution of Engineering and Technology.

Through over 30 years' work and investigation, he has developed a portfolio of research projects in mechatronic system design research including the development and application of "*mechatronic design process models*", modelling and simulation of these systems, and techniques in prototyping these systems for validation. He has recently built a strong research team after establishing SMeSTech research laboratory in 2012. He has managed over 40 projects in his research fields funded by the UK government funding bodies (EPSRC, TSB/InnovateUK, STFC), European Commission, international funding bodies and industrial partners.

He received his Ph.D. from Loughborough University of Technology and is a chartered engineer and a fellow of Institution of Engineering and Technology (formerly IEE) and a fellow of IMechE. His research interests include mechatronic systems design, robotics especially in recent years in space robotics, *Micro-mechatronic research and multi-perspective mechatronic system modelling, design and simulation,* computer support mechatronic systems design using AI techniques, knowledge-intensive product modelling and simulation, *the proactive computer support of product life-cycle synthesis* and *Product generalisation and configuration design and constraint based insightful engineering design support*.

He has organised and chaired four international conferences and published over 180 technical papers in major international journals and conferences and edited or written 6 books in related fields. He is an invited professor or visiting professor at 4 international universities, and he has been invited to give lectures at French, Japanese and Chinese Universities and various research institutions. He is the recipient of Judges Commendation Best KTP Partnership (Scotland) 2010 award and several best paper awards. He has also been a key team member for several industry best awards for some mechatronic products and systems.

Wenjing Zhao received the B.S. degree and M.S. degree (Mechatronics Engineering) from the University of Electronic Science and Technology of China in 2007 and 2010, respectively. She received her Ph.D. degree at the Department of Mechanical Engineering and Intelligent Systems from The University of Electro-Communications in Japan at 2014.

During the Ph.D., her research was primarily focused on the development of biomimetic soft underwater robots. She now is working at the College of Mechanical Engineering in the Zhejiang University of Technology in China. Her current research interests include soft robots, mechatronics, fluid–structure interaction system, friction and sealing, and other robotic technologies.

Chapter 1
Mechatronic Futures

David Bradley and Peter Hehenberger

1.1 The Challenge

The period of over 40 years since the concept of a mechatronic system was introduced by Tetsuro Mori [1] to express the growing impact that the availability of electronic components was having on the control and operation of inherently mechanical systems has been, and continues to be, a period of significant and rapid technological change. In particular, there has been a shift in emphasis within systems from hardware to firmware and software, leading to the introduction of a wide range of consumer products structured around the use of smart devices, many of which remain essentially mechatronic in nature in that they bring together a core of mechanical engineering with increasingly sophisticated electronics and software. When combined with enhanced local and remote communications, this has led to the evolution of systems based around the ability of smart objects to communicate with each other, and hence to effectively self-configure according to context.

This in turn has led to the development of concepts such as Cyber-Physical Systems, the Internet of Things and Big Data [2–11] in which interaction is driven through the combination of smart objects and information. Referring to Figs. 1.1, 1.2 and Table 1.1, users access cloud-based structures through smart objects to draw on resources provided by a range of, often unknown or invisible, sources.

The growth of provision represented by Table 1.1 has also led to a growth in availability of sophisticated user systems where, for instance, smartphones increasingly incorporate high-quality still and video imaging capability to the point where they are now responsible for more images than conventional cameras. It has

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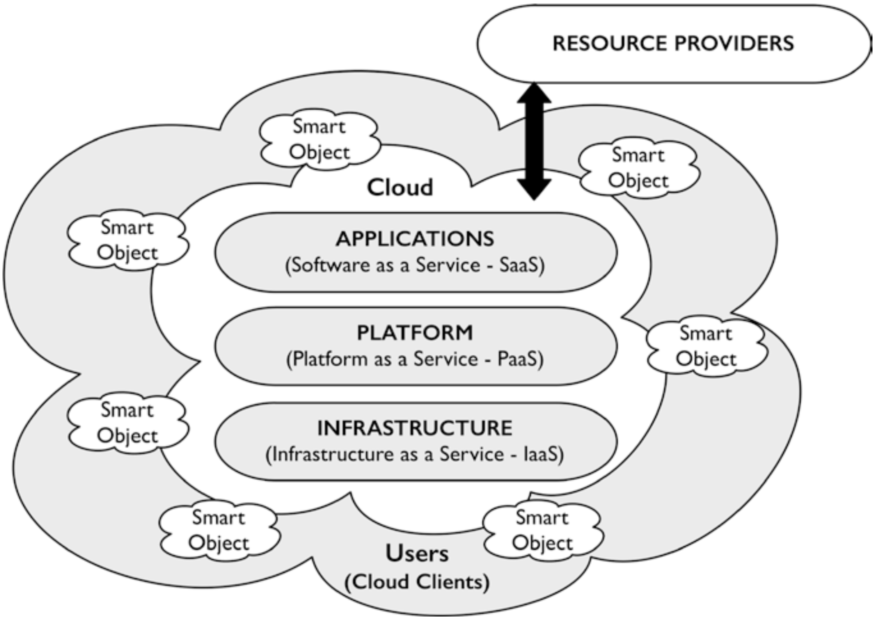


Fig. 1.1 Cloud-based structures for the Internet of Things

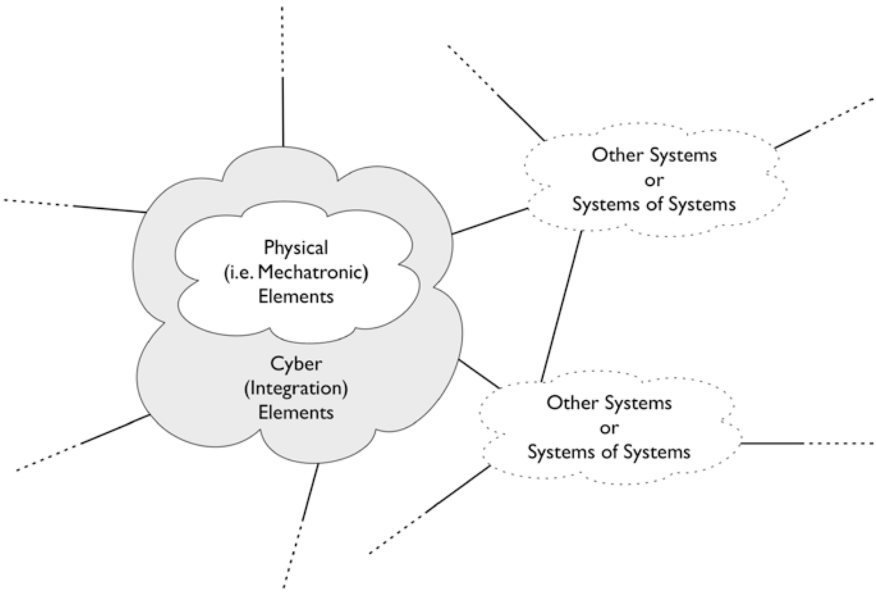


Fig. 1.2 Cyber-physical systems

Table 1.1 Cloud functions

Applications (software as a Service—SaaS)	Apps, Games, Mail, Virtual Desktop, Customer Management, Communications, Access, On-Demand Systems, …
Platform (platform as a Service—PaaS)	Runtime Operation and Management, Databases, Web Server, Tools, Computation, …
Infrastructure (infrastructure as a Service—IaaS)	Virtual Machines, Servers, Storage, Load Balancing, Networking, Communications, …

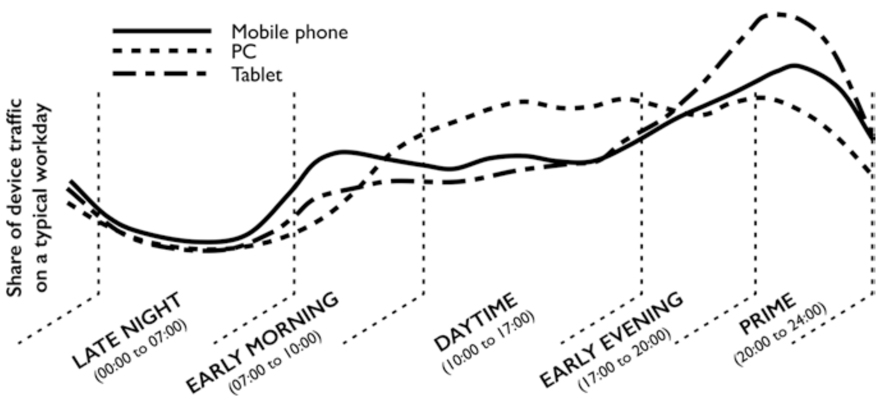


Fig. 1.3 Daily profile of use for mobile phones, PCs and tablets (after [12])

also led to the introduction of a range of user devices for behavioural monitoring, smart watches and tablet computers, all of which are capable of interacting with other smart devices through the medium of the Internet. Figures 1.3 and 1.4 together illustrate the daily profile of use for such devices [12–15]. All of the above have implications for the design, development and implementation of mechatronic systems, and for the future of mechatronics itself [16, 17].

In 2014, in association with the Mechatronics Forum Conference held in Karlstad in Sweden, a number of practitioners from around the world were asked to provide, in a single phrase, their view of the most significant challenges faced by mechatronics in coming years. The responses received are presented as Fig. 1.5 and will be discussed in more detail in the following sections of this chapter.

1.2 Challenges

Taking the above responses, the key issues can be summarised as:

- Design
- Privacy and Security

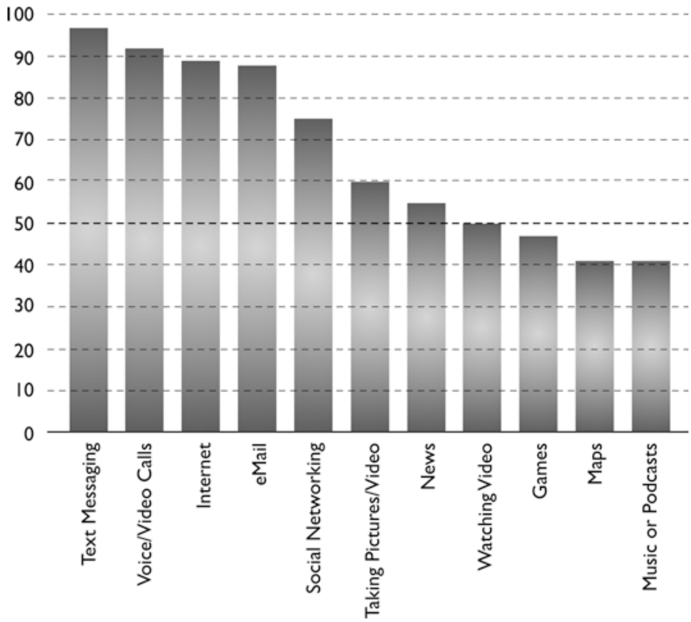


Fig. 1.4 Mobile phone use (after [13])

- Complexity and Ethics
- Ageing Population
- Users
- Sustainability
- Education

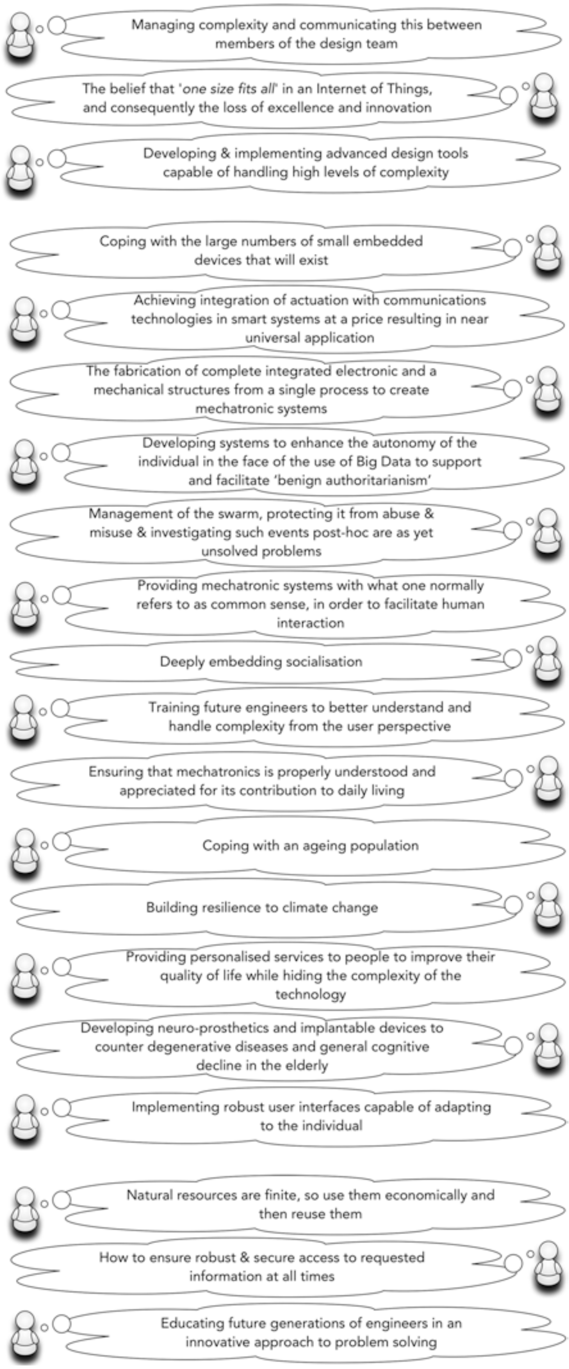
Each of which will be briefly discussed in the following sections.

1.2.1 Design

Conventional approaches to engineering design typically follow a path such as that defined by the simplified V-Model of Fig. 1.6 with integration being achieved through a structured system definition followed by a process of system development supported by appropriate testing regimes to support verification and validation. Individual modules and sub-modules, including those from external sources, are then tied into the design by a process of specification, test, verification and validation to ensure overall system functionality.

This approach has evolved over many years through the synergetic interaction between design theory and design practice. However, it is the case that design theory must inevitably lag behind practice where the possibilities afforded by new

Fig. 1.5 Practitioner responses regarding challenges facing mechatronics



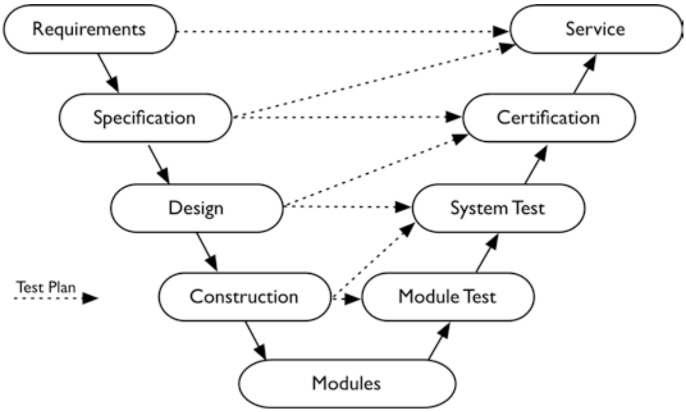


Fig. 1.6 Simplified V-Model

technologies are being explored, perhaps without necessarily a full understanding of their capability or implications.

In the case of the Cyber-Physical Systems and the IoT, the system is a dynamic entity which smart objects, and hence users, enter or leave depending on context and need. In the majority of instances, the cloud-based components will be unknown to the user prior to their being adopted for use, and the same may well apply to any functional smart objects. This leaves the designer with the issue of ensuring that the system is not vulnerable to their inclusion, while recognising the ability of the system to self-configure as required.

Essentially, therefore the user specifies system function and content after which the system autonomously configures selecting required software and data components from cloud with information then becoming a commodity whose value is determined by user context. Where physical components are involved, as for instance in a smart home environment, identification and selection will be by the user with guidance. A challenge for designers is to provide tools to enable the implications of the dynamic system configuration to be explored at the earliest stages of the design process, and to integrate these outcomes into device functionality as appropriate [18].

1.2.2 Privacy and Security

Many of the devices associated with the IoT have the capacity to gather large volumes of personal data, much of which may be held in areas and ways unknown to the user. This data is then subject to the possibility of analysis, with associated risks of misinterpretation impacting on privacy [20–23]. However, this must be balanced against the potential ability to extract beneficial knowledge, particularly

Table 1.2 Perceived threats to system security (after [19])

Threat	Probability (%)
Data leakage	17
Employee error	16
Employee-owned device incidents	13
Cloud computing	11
Cyber attacks	7
Disgruntled employee	5
External hacking	5
All of the above	19
None of the above	8

within the context of IoT-based applications such as eHealth [24]. In the wider context of security, the ability of systems to protect themselves against intrusion is of increasing importance, both at the personal and the corporate level. Table 1.2 shows the perceived levels of threat based on a survey conducted by the Information Systems Audit and Control Association [19].

It is therefore clear that there is an increasing burden on system designers to place privacy at the core of their design process within the context each of the Internet of Things, Cyber-Physical Systems and Big Data, and that this must be reflected in the design process itself and the methods and tools to support this.

1.2.3 Complexity and Ethics

As systems become increasingly complex and begin to operate with greater autonomy, issues are raised regarding the ability of all stakeholders to understand their nature and function across a range of applications and environments from healthcare to autonomous vehicles [25–28]. This is particularly the case where responsibility for the wellbeing, or indeed the life, of an individual or individuals is being entrusted to the system [29]. Other issues include:

- Dual-use of technology—Technologies such as drones can be associated with beneficial applications, as for instance in crop management, but also for military and other purposes.
- Impact of a technology on the environment—The introduction of technologies into an environment can disrupt and change that environment in a variety of ways, even when the underlying intent is benign.
- Impact of technology on the global distribution of wealth—The use of technologies can increase the separation between differing societal groups, even within the same country [13].
- The digital divide and the associated socio-technological gap—There is an increasing separation between the ability to access and use the services provided through the cloud.

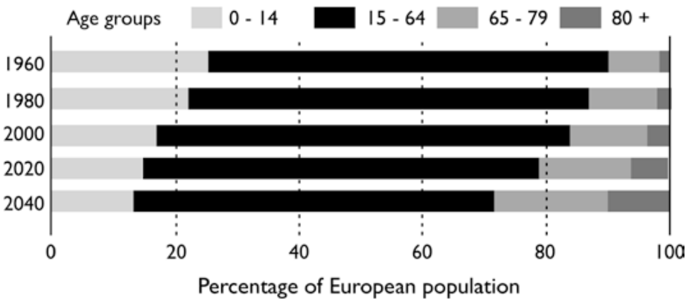


Fig. 1.7 An ageing population in Europe (after [32])

- Ensuring fair access to technologies—Controlling access to technology can act as a restriction on development.
- Technological addiction—Individuals becoming addicted to the technologies that they use [30].
- Technological lock-in—Individuals can become locked into specific technologies, a simple example being the choice between Apple and Android.
- Dehumanisation of humans and anthropomorphism—By taking away responsibility for their activities and wellbeing [31].

1.2.4 Ageing Population

Faced with an ageing population, Fig. 1.7 shows the past and predicted changes in the distribution of age groups within Europe,[1] questions are raised as to how best to use technology to support the elderly, and to try to provide them with increasing levels of independence in old age. In particular, there is a need to ensure appropriate levels of mobility within both the physical and information domains to prevent individuals retain independence and engagement with society [33, 34].

1.2.5 Users

As has been seen, the availability of Internet-capable devices has had a significant impact on social behaviour through the use of social media, but also allows a much more ready access to information than has historically been the case. Such devices also support increased levels of interaction with the environment, as for instance in the case of a smart home. Additionally, the introduction of wearable

[1]Similar data can be found for other global regions.

devices provides opportunities for developments in areas such as eHealth and mHealth to support individual wellbeing [35], in turn raising issues of privacy and the control of personal data.

However, there is also a need to develop new forms of user interface to support a wider range of users in their ability to interact with such systems. In particular, there is an increasing requirement to be able to capture user intent and context in a way which does not require complex forms of communication or knowledge about the underlying technology.

1.2.6 Sustainability

There is a recognised need to move towards more sustainable forms of society-centred around the individual and their needs and structured around the effective management and use of all available resources as suggested by Fig. 1.8. In the context of mechatronics [36, 37], this integrates into concepts such as those of the smart home and the smart city where information is used to manage daily activities.

For instance, it is estimated that, on average, finding a parking place in a German city requires about 4.5 km of driving which for a vehicle emitting around 140 g of CO_2/km will generate at least 630 g of unnecessary CO_2, and significantly more in stop-and-go traffic. By linking knowledge of available parking spaces with the vehicle destination through appropriate communications, much of this excess could be eliminated [38]. Other sustainability issues impacting on cities are suggested in Table 1.3.

Overall, therefore there is a move towards the creation of sustainable societies with individuals and the core to address issues such as ageing populations, resource availability and management, climate change and resilience [40–44]. Referring to mechatronics and the Internet of Things, an underlying requirement

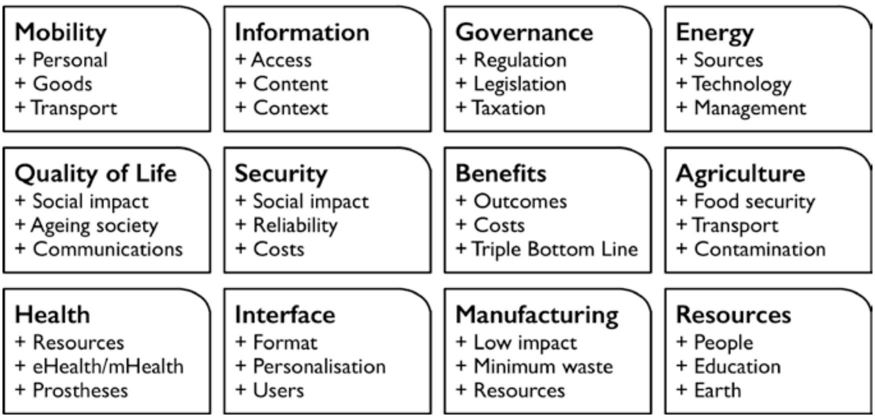


Fig. 1.8 Sustainability domains

Table 1.3 City problems (after [39])

	US/Canada	Europe	Asia	Latin America	Africa
Average population (millions)	1.4	2.5	9.4	4.6	3.9
Population density (per km^2)	3100	3900	8200	4500	4600
Water consumption (litres per capita per day)	587	288	278	264	187
Water loss rate (%)	13	23	22	35	30
CO_2 emissions per capita (tonnes)	14.5	5.2	4.6	No data	No data
Waste volume (kg per capita per year)	No data	511	375	465	408

in achieving sustainability is the effective management and use of all resources; technical, physical and human, through the integrated use of information serviced by a range of smart objects.

This in turn implies the effective and appropriate use of information to support the engagement of individuals in all aspects of their lifestyle through the adoption of novel and innovative approaches to understanding, structuring and managing the physical and information environments, and the relationships between them, as part of a knowledge economy configured around the Internet of Things. Consider two different urban scenarios as follows:

Scenario 1: *New Build*—The aim is to achieve integration of the physical and information environments from the outset, supported by access to facilities such as high-speed broadband networks and the ability to deploy a full range of smart technologies within those environments.

Scenario 2: *Established Communities*—These represent the majority of the population and means that the introduction of infrastructure changes will need to take account of the impact on the existing environment, and the adaptation of that environment to the needs of technology.

1.2.7 Education

Mechatronics education has always faced the challenge of balancing appropriate levels of technical content with the understanding of the requirements for integration across the core disciplines of mechanical engineering, electronics and information technology [16, 17, 45–47]. Given the growth in the technological base over the last 40 plus years as suggested by Fig. 1.9 [17], the challenge facing mechatronics course designers in achieving that balance has become significantly more complex.

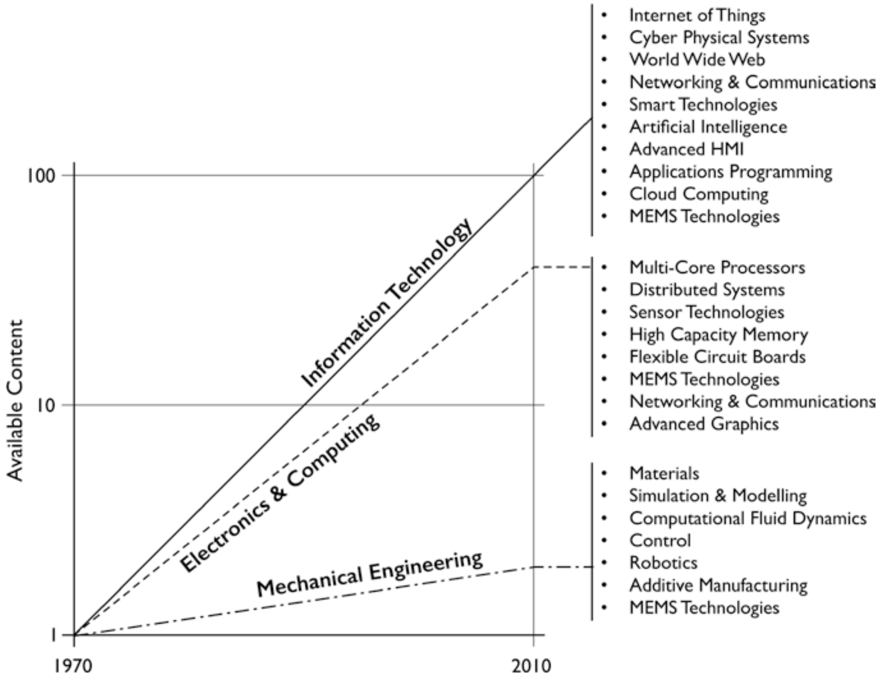


Fig. 1.9 Development and diversification of mechatronics technologies (after [17])

Fig. 1.10 The challenges of innovation

In addition to the challenges to course design associated with developments in technology a number of other factors need to be taken into account. These include:

- Changes in delivery
  – Massive On-line Open Courses (MOOCS) [48].
  – Tutorial and workshop based learning support.
  – Blended learning [49].
  – Impact of social media on learning [50].
- Structural Issues
  – Distributed learning resources.
  – Time value of content.
  – Collaborative working.

A key element for the future is therefore that of encouraging an innovative approach to mechatronics through education (Fig. 1.10).

1.3 Chapter Structure

The book is structured around a series of chapters from invited authors, each of whom is an expert in a particular area of mechatronics. In each case, the authors were challenged to establish the current state of the art using their own research or professional expertise as the starting point and then to try to isolate and identify those key areas in which significant development is needed or likely to take place in coming years. The chapters themselves are organised as set out in Table 1.4.

1.4 Summary

Though the core technologies and concepts remain essentially unchanged, the nature of what constitutes mechatronics has changed significantly since the concept was originally proposed, and that change is likely to continued at an accelerating rate. Some of the issues and challenges be addressed have been identified in the preceding sections, and will be developed and expanded in subsequent chapters.

Table 1.4 Chapter structure

Chapter(s)	Subject area
1	Introduction
2 and 3	Issues and Challenges
4–8	System Design, Modelling and Simulation
9	Manufacturing Technology
10–12	Internet of Things and Cyber-Physical Systems
13	Communication and Information Technologies
14 and 15	Mechatronics Education
16	Conclusions

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Chapter 2
Mechatronics Disrupted

Maarten Steinbuch

2.1 How It Started

The field of mechatronics started in the 1970s when mechanical systems needed more accurate controlled motions. This forced both industry and academia to explore sensors, and electronic assisted feedback, while using mostly electrical drives instead of, for instance, mechanical cam shafts in production facilities. This introduction of feedback-controlled motion formed the basis for the need to enable mechanical engineers and electronic engineers to work better together and to understand each others language. Note that in those days control engineering departments were mostly part of the electrical development or research departments of industry and academia. Various initiatives were also undertaken to develop a common language or methodology. Some institutes pushed mechatronics forward as being a new discipline.

In industry, the design teams were typically forced to really discuss at the specification level deeper insights from within their specific disciplinary knowledge. Computer-assisted design and simulation tools really boosted the field in the late 1980s and 1990. An example of the project-oriented mechatronics way of working has been the development of optical storage devices such as that of Fig. 2.1 [1]. Teams of mechanical designers, using their finite element programs, and electronics and control specialists, with their specific simulation tools, codeveloped mechanisms with very tight specifications on manufacturability, cost and dynamics.

In that same time frame of the 1980s, in many industries and academia, mechanical engineers started more and more to also address dynamics and control, and control groups started to emerge also in mechanical engineering departments, all of which signalled a move away from the mono-disciplinary approaches of Fig. 2.2 [1].

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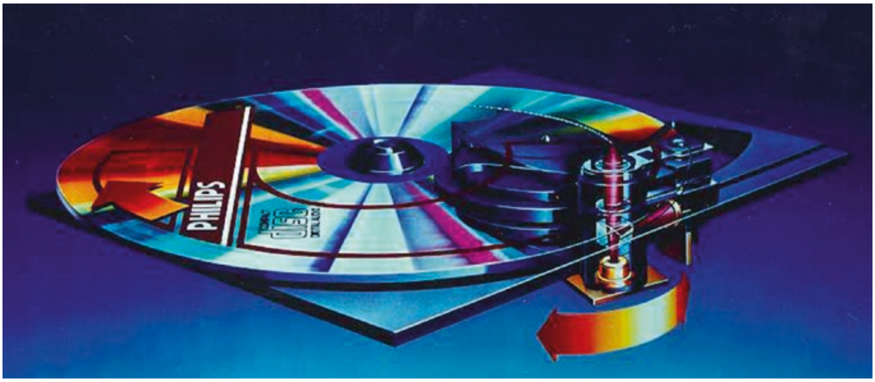

Fig. 2.1 An optical storage device with a balanced rotating arm by philips electronics NV

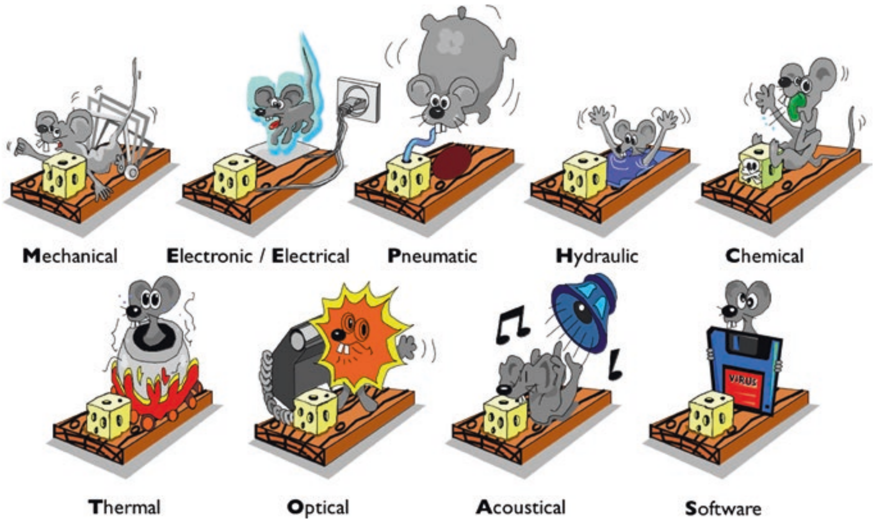

Fig. 2.2 Many mono-disciplinary solutions for a given problem [1]

2.2 Computer Controlled Devices

The rapid development of the personal computer, enabled the better use of simulation and design tools, and hence improving the overall design process and quality of exchange of design ideas in an early phase. However, and equally relevant, the PC-enabled digitized computer controlled mechatronic systems testing and implementation. This required addressing the role of computer science engineering and showed the need to include the software discipline, but to a still rather limited extent. This also led to include more and more the field of systems engineering as a way of working in industry on more complex products and high tech systems. However, thinking about the 'common' language, or at least to understand each other better, clearly is far less trivial between the hardware and software domains, than within the hardware domain itself.

From a research perspective, the questions start at the discrete time level, i.e. how to the use the computer to implement control functions such that the performance previously done with analogue implementation was maintained as much as possible. However, soon the higher level supervisory control modes were taken into the mechatronics field, and this forced research to make the switch towards the much more difficult questions of discrete event systems, facing continuous time dynamics in the mechanical system. This has led to the research field of hybrid systems within the systems and control discipline. This part forms the natural interface between the hardware (the '*old*' mechatronics) and the software (computer science) field.

2.3 Applications

The performance improvements due to mechatronic thinking have been profound and are broadly acknowledged. Applications of mechatronics can be found in many products and production environments. Although in the early days, the control of electric motors was an often seen application, mechatronic thinking also is used in the design of hydraulic systems, piezo driving actuators, the modelling and control of production equipment, scientific equipment, opto-mechatronics, automotive mechatronics, etc.

Overseeing the inflow of submitted mechatronics papers over the last few years, more application papers are submitted on medical devices, on high precision systems, drones (UAV), automotive and robotics. The papers on scientific achievements on modelling languages and tools have reduced, meaning probably that appropriate tooling is now more common. The same seems to be true for papers on education in mechatronics. This was a hot topic in the late 1990s, where good examples were found including experimental work for the students.

There are not so many discussion papers anymore about what could be called the mechatronic design method, because it is by now maybe clear that part of the innovation done in mechatronics in practice has more to do with helping disciplines to communicate, preferably via the use of shared models or quantified simulations. The scientific methods addressed in mechatronic journal submission are mostly seen in the systems and control area, where the mechatronic application is often used as a validation or simply as a show case. An emerging field is the use of optimisation algorithms, not only for finding optimal control laws, but more and more also for component design, up to system topology optimisation as a new design tool [2]. The core of the mechatronic submissions and community still is Mechanical Engineering, Electrical Engineering and the area of Systems and Control. The interrelation with Computer Science and Physics is still rather limited, but this is going to shift to coming years.

2.4 Multi-physics

High-end mechatronic systems such as wafer scanners such as that of Fig. 2.3 for optical lithography or electron scanning probes and in space applications and scientific instrumentation, have an error budget that is getting closer to being a flat distribution over the various sources.

For instance, for modern wafer scanners thermal and cooling-fluids-induced vibrations now are as significant as mechanical modal vibrations excited by the actuators. This has to do with the extreme conditions and requirements; moving an 80 kg mass with accelerations more than 10 g, and achieving accuracies below nanometres with mKelvin temperature variation [3]. This means that the '*normal*' mechatronics and its motion control systems now start to have a dynamic interaction with the thermal and fluid control dynamics. The overall performance assessment and design improvements now start to cover not only mechanical and electrical/electronic and software disciplines, but also physics issues like thermal and fluid partial differential equation-based modelling. And what will be the impact for mechatronics design thinking when we include the possibilities of additive manufacturing? If a 3D industrial metal or ceramics printer can be used to freely shape our mechanisms, how to arrive at an overall optimal design?

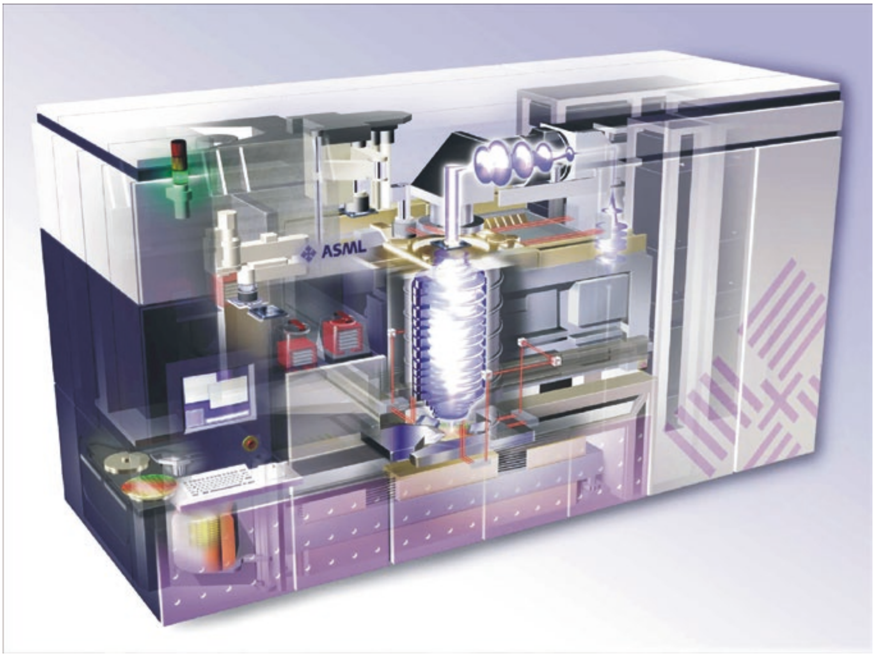

Fig. 2.3 Wafer scanner

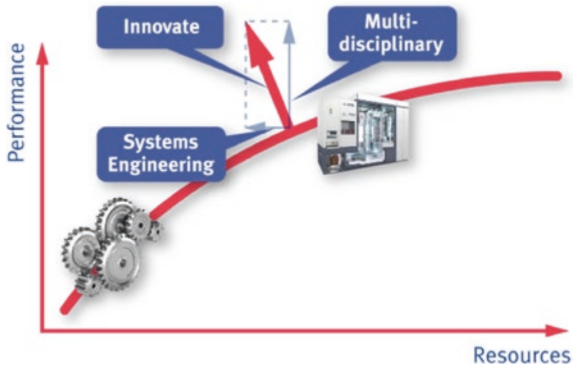

Fig. 2.4 The performance complexity (resources) trade-off [4]

The performance trade-off can now only be lifted to the next level if we are able to handle this complexity by proper systems engineering and the inclusion of more disciplines.

In Fig. 2.4 this trend is depicted in the form of a performance versus resources plot. Resources could be money, people, development time, computer power, energy, etc. The performance typically is accuracy, throughput and robustness/reliability. The curve shows that achieving more performance does cost more and more resources, until not feasible. In the figure, examples are also plotted; first, a simple transmission gear system, having low performance (in terms of accuracy) and also requiring limited resources. The second, example in the figure is a modern wafer scanner as the example of extreme performance and needing huge resources.

The curve implies that in order to further boost innovation, we need to incorporate two means. First, by addressing all relevant disciplines, so including for instance physics, we will be able to increase performance. Second, by introducing a systems engineering approach we can handle complexity in a better way, and hence, go left on the resources axis.

2.5 Robotics

Almost opposite to the high-end systems as described above, the robotics field also influences the mechatronics area. Here, it is not the multi-physics discipline that is required, but the computer science field to cope with unstructured and changing environments. In robotics, the developments are directed towards vision, mapping, and localization, so understanding the environment (‘*world modelling*’) but also the field of Artificial Intelligence (AI)—which has already been a promise for decades, but could evolve rapidly in coming years. Both areas are currently in an accelerating phase because of the upcoming autonomous vehicles. The disruption seen in the automotive industry is huge, both in the area of power trains

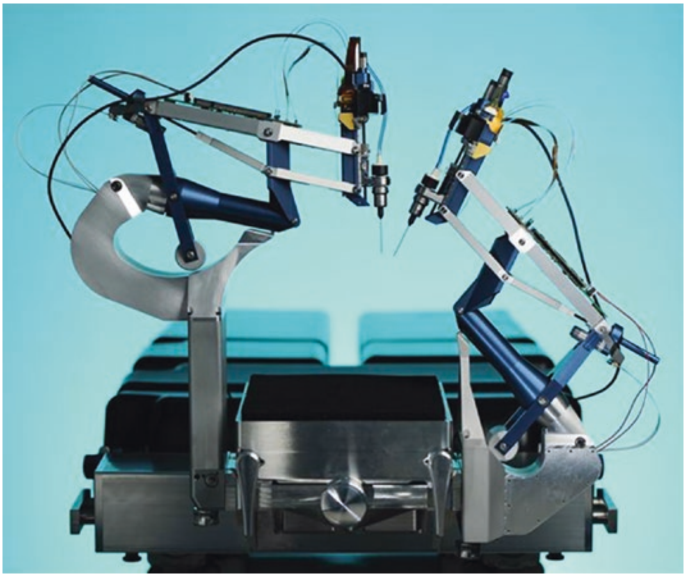

Fig. 2.5 The *Preceyes* eye surgery robot [5]

(i.e. electric drives and transmissions), and the use of computer science, as for instance the sensors in a modern car, including the rapid developments in autonomous functions implemented in passenger cars as well as in commercial vehicles. This in fact is all about mechatronics, AI, controls!

The field of robotics, including autonomous cars, could be treated as a separate research area, next to mechatronics, but for instance the speed requirements of industrial robots or the accuracy requirements of surgical robots such as the *Preceyes* robot of Fig. 2.5 necessitate the inclusion of the description of the dynamic behaviour of the robots. The change from rigid body modelling towards flexible systems, then directly makes it in the heart of mechatronics. The same holds for the systems engineering thinking and the system topology optimization, which is also similar in hybrid power trains for vehicles. So where does mechatronics end and robotics start?

2.6 Cyber-Physical Systems, Smart Industry and the Internet of Things

The shift from decentralized mechatronic systems towards networked connected systems is known as the field of cyber physical systems, referring to the field of cybernetics. The research questions are how to guarantee stability and performance during or after packet (information) loss, and how to deal with variable delays. The domain is even further away from the hardware of mechatronics, but is developing so rapidly, that we should ask the question how to embrace to potential of network-controlled systems, for instance in the field of remote condition monitoring and servicing. In the next decade, the explosion of the Internet of Things (IoT) further necessitates finding the answers to this question [6].

One application where mechatronics will meet IoT is in the future of our manufacturing. The Industry 4.0 or Smart Industry attention is about networked modern industrial automation.

- What does it mean for the flow of goods through a manufacturing plant if knowledge of the logistics is shared, if the performance of one workstation is optimized as part of the total logistics or operation, if service and repair in a production facility is robust because workstations are flexible and can adapt?
- What does this imply for the industrial robotics and smart mechatronic production devices?
- How will this impact the design requirement of our mechatronic devices and products?

The Internet of Things will not only change the modern factory. It is estimated that in 2020, 50 billion devices will be connected to internet. This means it will be entering our households and equipment used at home, as well as our cars. When wearable electronics are pushed further, and we are surrounded by sensors, we only need the step towards actuation to be able to closed the loop and by that enter the world of mechatronics again [6]!

2.7 Towards Systems Integration

Overseeing these developments we could question what mechatronics actually is or will be. Is mechatronics being disrupted? Has it evaporated already into systems engineering, is it part of the supporting disciplines, does it enlarge to be the backbone of cyber physics? Moreover, if biological systems are also going to have technical devices implemented (Internet of Humans), what is then the role of the mechatronics discipline? How should we educate people in mechatronics thinking, how small or how broad? In Fig. 2.6 the role of systems engineering is used to enable the necessary integration of the disciplinary as well as the technological contributions.

In this book many of the mentioned developments will be addressed. We will not have definite answers for the future of mechatronics, nor for its education, but we learn also that this should be robust and adaptable because we cannot predict the future! We know for sure that the pace of technological development is accelerating, hence, so should we!

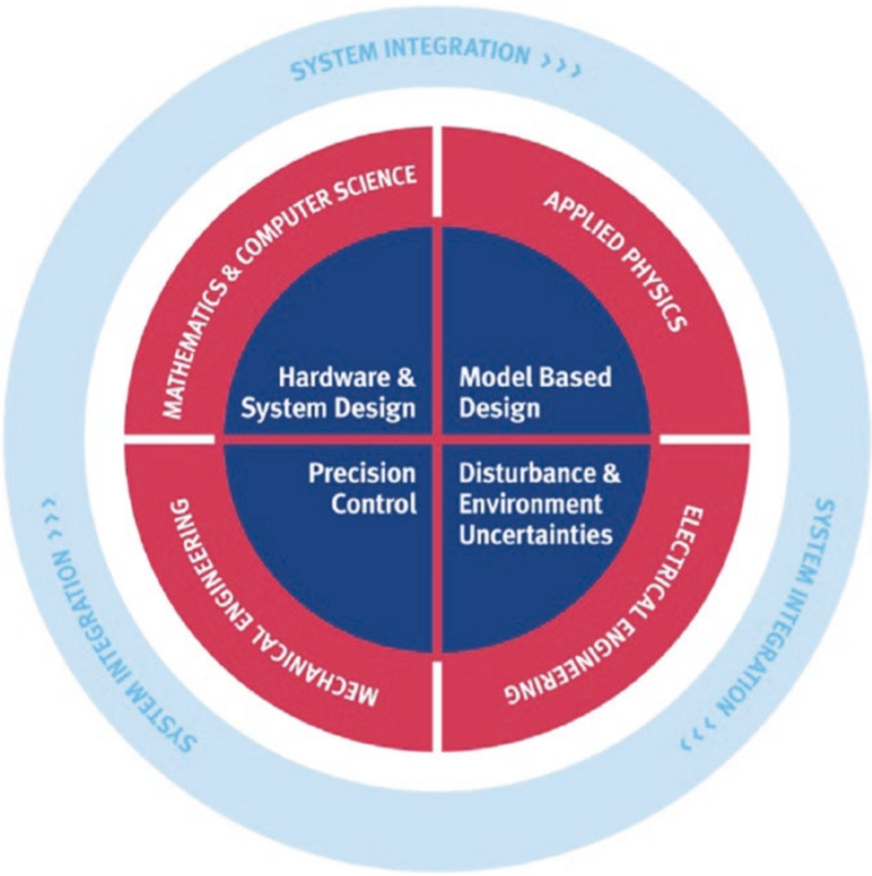

Fig. 2.6 Systems engineering integration of disciplines and technologies [4]

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Chapter 3
Future Challenges in Mechatronics

Nicolas Albarello, Alexandre Arnold and Marc Budinger

3.1 Introduction

In the aerospace industry, mastering the design of mechatronic systems is a major requirement. Indeed, a big part of programme cost is spent on the design of these systems, which also represent a big part of the product performance. In this chapter, some of the main challenges that industries will face in coming years in the field of mechatronics are exposed. These challenges deal with the design of mechatronic systems, their verification/validation and their operation.

3.2 Challenges in Design—Architecture and Sizing

3.2.1 Using Models to Size an Architecture

The physical architecture of embedded technological systems such as the electro-mechanical actuators of flight control systems, Fig. 3.1a [1] or power electronic modules of supply network, Fig. 3.2b [2], are an association of components from different technologies.

Work by Van der Auweraer et al. [3] and Hehenberger et al. [4] highlights that the design of such multi-domain systems requires different modelling layers as represented in Fig. 3.2:

- A mechatronic layer has to take into account the functional and physical coupling between components. This level of modelling is usually done using 0D/1D

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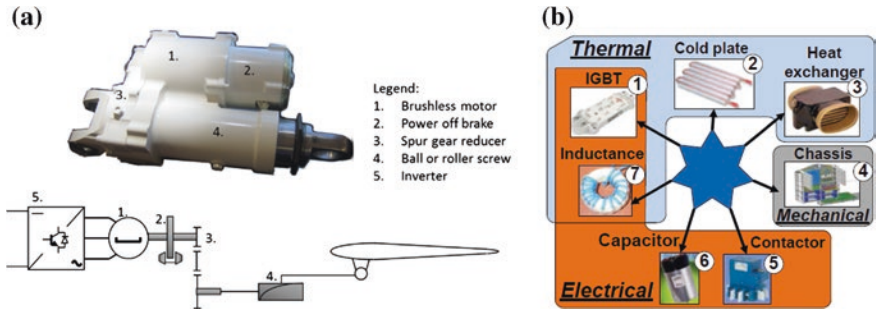

Fig. 3.1 Multi-domain architecture of an embedded system

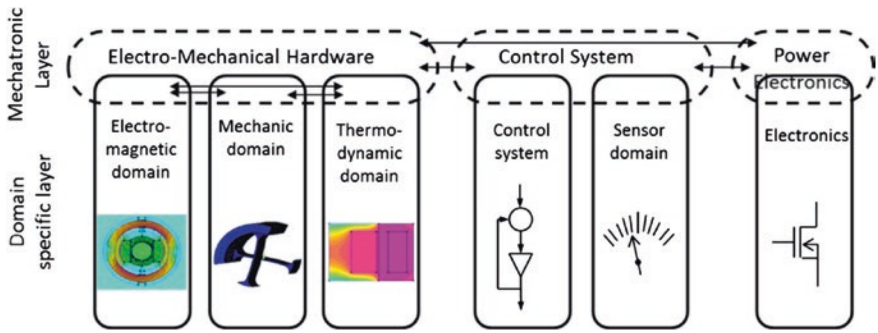

Fig. 3.2 Hierarchical design models (after Hehenberger et al. [4])

models [3], also called lumped parameter models, represented by algebraic equations, ordinary differential equations (ODE) or differential algebraic equations (DAE).

- A specific domain layer to describe the performance limits and parameters is necessary in the previous layer, based on a geometric representation. The specific domain phenomena are generally represented through partial differential equations (PDE). This level of modelling can be achieved for simplified geometries using analytical models or, for complex 2D and 3D geometries, for instance by using numerical approximations such as finite element methods (FEM).

The design of the power element with a system integrator's point of view should allow for the optimizing of the size and specification of components from multiple technologies interacting together. This system-level design, distinct from component design, needs to represent in the mechatronic layer the key information of the specific domain layer with dedicated models [5–7].

Referred to as "*estimation models*" by Budinger et al. [7], they enable the designer to readily take multiple design constraints into account. The models directly and explicitly link a few primary characteristics, such as overall dimensions of components, to the secondary characteristics needed for the sizing [5] and optimization [1]. The capacities required of these estimation models are as follows:

- To present a form that is simple to handle and to implement in different calculation tools.
- To lend themselves to easy analytical manipulations.
- To be reusable in an area slightly different from the one where they were initially employed.

To satisfy these constraints, simplified analytical models are often used. Among these, scaling laws have proved effective in representing a physical phenomenon over wide ranges of variation [6]. However, these models are only valid under certain conditions, among which one can mention geometry and material similarities and uniqueness of the driving physical phenomenon.

For the system designer the models should be as predictive as possible. Detailed finite element models, able to precisely predict the physical phenomena, are still much time-consuming in such a context. Despite a recent thrust of work on model order reduction, the computational cost of finite element models remains prohibitive in the preliminary design phase. The use of meta-modelling techniques [7, 8] is thus interesting for this purpose. A challenge for mechatronic design is the development of meta-modelling techniques specifically dedicated to the selection of components of system from an integrator point of view. A paper by Budinger et al. [7] proposes a meta-modelling method based on scaling laws which extract simple, global expressions of estimation models from local numerical simulations (FEM).

3.2.2 Coupled Disciplines for the Design of Mechatronic Systems

The design of systems as those in Fig. 3.1 is driven by the following main aspects to meet the various requirements: integration (mass, geometrical envelope) between airframe and actuated load, resistance to environment (thermal and vibration), instant power and energy saving, dynamic performance, service life, reliability, resistance to or tolerance of failures. Table 3.1 summarizes these different design viewpoints and the possible associated modelling levels for a model-based design.

These multiple design viewpoints generate real challenges when optimizing such systems. To take account of these criteria in the same loop, tools coming from multidisciplinary design optimization (MDO) can be useful [8]. MDO is a field of engineering that uses statistical and optimization methods to solve design problems incorporating all relevant disciplines represented by 2D/3D FEM

Table 3.1 Design views and associated modelling levels during design of mechatronics systems, an example of a flight control actuator

Requirements	Corresponding design or sizing viewpoints	Algebraic models (0D)	Differential algebraic (1D) equations	CAD (3D)	FEM (3D)
Integration	Mass	⊗		⊗	
	Geometrical envelope	⊗		⊗	
Mechanical resistance	Transient stress		⊗		⊗
	Fatigue/Thermal/Wear stress	⊗	⊗		⊗
	Vibration	⊗	⊗		⊗
Reliability	Life time/MTBF/Failure rate	⊗	⊗		
	Failure/Critical cases: winding short circuit, jamming, shock		⊗		⊗
Dynamic/Control	Natural modes	⊗	⊗		⊗
	Bandwidth		⊗		
	Precision	⊗	⊗		
Power/Energy	Transient input power	⊗	⊗		
	Energy consumption	⊗	⊗		

analyses, 0D/1D simulations and algebraic calculations simultaneously. Each specific computation is considered as a black box which can be called directly, analysed with design of experiments (DoE). All calculations can be linked together and used for design exploration, sensitivity, optimization and robustness analyses; i*Sight* [9], *Optimus* [10] and *ModelCenter* [11] are examples of such frameworks.

Optimization tasks require a small computational time for the models. The surrogate models or meta-models [8], simplified or approximate descriptive model of another model, can be used for representation of specific domain layer models (FEM) into the mechatronic layer. The mechatronics layer generally treats dynamic systems in the time domain and uses transient time simulation but methods relying on approximating the time domain behaviour by evaluating the dominant harmonics of the load profile [12] can be attractive during optimization of the design.

These optimization and statistical enabling tools allow the steps of the design process to be linked in a freely chosen sequence. They do not, however, provide help in choosing how the connections in the calculations are structured, or which parameters are to be taken into account as design parameters, constraints or objectives.

Knowledge-based engineering (KBE), a discipline which combines knowledge-based approaches and computer-aided design, can also be useful for design support. KBE software packages are dedicated to centralizing all the know-how and expertise for the design of a specific product. Scientific concepts and methodologies used in these environments are as follows:

- Knowledge bases and computer-aided design: the knowledge of the components is capitalized with un-oriented algebraic equations (declarative approach) [13]. These components can be easily assembled to describe different architectures.
- Constraint networks, graph theory and optimization: the set of equations initially defined in declarative form is oriented in order to obtain a calculation procedure usable by an optimization algorithm.

The adaptation or analysis of the equations may be supported by symbolic computations, interval calculations or artificial intelligence. These KBE tools can be:

- Linked to a CAD software as in *Genus Designer* [14] which captures the configuration rules and performs process automation for *Solidworks*;
- Dedicated to a specific domain as in *Enventive* [15] for the conceptual design of planar mechanisms (optimization, tolerance, sensitivity analysis);
- Developed over several domains, as in the case for FST institute software (TUHH University) which, from the same basis, supports the preliminary design of lift mechanisms [16], hydraulic networks [17] and EMA of aircraft;
- General, such as *TKSolver* [18], *Ascend* [19], *Cades* [20], *Design 43* [21] or *PaceLab* suite [22] and are often declarative language that enables a set of algebraic equations to be used with different inputs depending on the design objectives.

These tools can provide interesting and important help for the designer especially when the system becomes complex with multiple technologies. Paired with MDO tools and dedicated meta-modelling techniques, they might represent the future of the design of mechatronic systems.

3.2.3 Ability to Synthesize Optimal Architectures

When designing a mechatronic system, numerous solutions can be envisaged at the architecture level. The task of selecting the most appropriate architecture is a complex task that is currently mainly done by manually defining, assessing and comparing envisaged architectures. The use of design synthesis and optimization techniques at the architecture level permits the designer to envisage a broader range of solutions, among which are potentially innovative ones, and to compare them on a formal basis (using well-defined metrics) in order to select the most appropriate one.

Engineering design synthesis [23] is a set of techniques that leads to the synthesis of engineering artefacts (2D/3D shapes, architectures, etc) based on knowledge about the purpose of the artefact, its expected properties and design knowledge (explicitly formalized or extracted from prior designs).

Optimization techniques iteratively modify some initial solutions (generally randomly generated) in order to optimize the characteristics of the tested solutions. However, they barely consider design knowledge in order to generate feasible solutions.

Coupling design synthesis and optimization permits generation of feasible solutions and the finding of the most performing ones. It is generally more efficient than a manual process since the explored design space can be larger and since the process is not influenced by cognitive biases (e.g. beliefs). However, this requires an ability to assess any generated solution along with all the defined selection criteria (optimization objectives/constraints). Examples of the use of this type of techniques are for the design of robot arms [24], vacuum cleaners [25] or aircraft cockpits [26].

3.2.4 Study of Safety and Availability in Mechatronic Systems

Reliability, Availability, Maintainability and Safety (RAMS) criteria are often part of the study carried out during the design process. A number of such studies must be performed for each considered alternatives in order to quantify the performances of the different architectures with respect to these criteria (reliability, availability, maintainability, etc).

Currently, these studies are carried out by specialists who build RAMS models of the mechatronic system and run analyses on them to generate conclusions. RAMS models are typically built using dedicated formalisms such as Petri nets, Bayesian networks, reliability block diagrams or more advanced languages such as *Altarica* [27] and *Figaro* [28].

In order to speed up the studies, it would be an advantage to link RAMS studies to (descriptive or behavioural) architecture models. Indeed, much information embedded in design models can be reused during RAMS studies.

A first approach considers enriching design models with RAMS data (failure modes, reliability rates, etc) in order to be able to automatically generate RAMS models. For instance, SysML [29] models (with a specific profile) can be used to automatically compute the system-level failure rates [30].

Another approach considers linking design models to RAMS models in order to ensure the consistency of the RAMS model. In the frame of the MODRIO project [31], a prototype was developed to automatically generate Figaro models from *Modelica* [32] models and a *Figaro* knowledge base [33]. *Modelica* specific constructs are used to declare the correspondence with a Figaro block from the knowledge base and other necessary information.

3.2.5 Functional Virtual Representation of the Product

The design and the integration of mechatronic systems is a multidisciplinary design process which requires multiple domains to collaborate and exchange information. In today's very large companies and in the extended enterprise, mastering these information flows becomes essential for the efficiency of the design phase.

One way of improving the communication between teams is to share a common virtual representation of the product that integrates all viewpoints. This representation permits the different teams to have a view on other team's constraints, and to always have access to the latest version of the design. Also, it enables the consideration of impacts from other domains during simulations.

An integrated view would also provide a more robust basis for decision-making since it would permit to have a view of all constraints and objectives of all concerned disciplines.

The main technical enablers for this type of representation is the capability to exchange engineering data between different teams working with different tools and data formats and the capability to integrate models coming from different disciplines.

3.3 Challenges in Verification and Validation

3.3.1 Ability to Virtually Validate a System

The verification of mechatronic systems is a very expensive task for industrials (especially in the aerospace industry). Indeed, it requires both the systems to be available and the development and manufacturing of test benches that are often not reusable from programme to programme. A means to reduce the cost of testing is virtual testing. This practice aims to develop virtual means (system models and system simulation environments) to test a system and verify its conformity to requirements. For instance, tests on real wings can be replaced by finite element models.

The main benefit of virtual testing is cost, since virtual test benches generally cost much less than real test benches and are often reusable from one programme to another. Indeed, many systems are similar from programme to programme and their models can in general be adapted to meet the new design with a limited effort.

A less obvious benefit is that virtual test benches permit the stimulation of the system in conditions that are closer from the real stimulation that the system will encounter during its lifecycle. For instance, on a wing bending test, loads are applied locally on the real test bench while they can be applied uniformly on the virtual one, thus representing real loads in a more accurate way. Some aspects (e.g. thermal effects) can be also considered more easily in a system model while they require very expensive means of testing if a real test is envisaged.

To enable virtual testing, several aspects of the verification process must be well managed. First, of course, the validation of the model and of its simulation environment must be carried out. This can be done by comparison of results with test bench data or flight test data. In this aspect, model calibration and uncertainty management techniques are required.

3.3.2 Formalize Model Requests to Model Suppliers

More and more, models are used to perform verification and validation (V&V) activities on systems. These models are often designed by the suppliers of the system (internal or external customers). However, being able to state what is expected from the model in terms of functionalities, domain of validity, precision, etc is still a challenge. Indeed, the requester has a view on the overall simulation environment (i.e. other interacting models, simulation inputs, etc) that is rarely communicated to the model developer in a formal way. This often leads to several iterations before the expected model is actually supplied to the model requester.

Recently, a model identity card was proposed as a standard description of model requests [34]. The MIC permits to describe some of the desired characteristics of the model in order to guide its development. First, interfaces of the model must be defined describing ports of the model and exchanged variables. Secondly, four sections of model information must be filled in as follows:

Object—model name, granularity level, reference documents
Object context usage—time computation, tool
Method—model dimension, method, linearity
Model quality—accuracy, verification, validation

Another potential use of this type of standardized model specification is the reuse of existing models. Indeed, formalizing the characteristics of a model enables posterior searches in model databases and reuse of models in different contexts.

3.3.3 Ability to Exchange and Seamlessly Integrate Models Between Industrial Partners

In relation to the objective of building multi-system simulation platforms to verify mechatronic systems, a major element is the ability to exchange and integrate models. Currently, model integrators tend to force their suppliers to use one tool and to follow specific modelling procedures (e.g. AP2633 [35]). On their side, model suppliers would like to use their own tools to model the system. Being able to exchange and integrate models coming from different tools would thus be off great advance.

The functional mock-up interface (FMI) initiative [36] goes in this direction by providing a tool-independent standard for the exchange of dynamic models and for co-simulation. It permits the generation of "*neutral-format*" models (under the form of a C-code and xml[1] files) that can be seamlessly integrated in compatible platforms. Currently, around 70 tools are supporting the standard.

The use of these standard model exchange forms provides flexibility since the constituent models for a simulation platform can be developed in a number of different tools. The model providers are thus free to choose and change their preferred tool without impacting on the overall simulation framework. On the side of model integrators, flexibility is also ensured since the integration platform can be chosen and changed among a set of available tools without impacting existing models.

This type of standard might also replace a lot of the point-to-point interfaces between tools that are developed in-house for specific needs or sold by tool vendors. For companies, it can represent huge savings in development or licensing costs.

3.3.4 Formal Verification of a Mechatronic System Through Models

Detection of system flaws in the very early design phases has always been at the core of model-based systems engineering (MBSE) to reduce global development time while increasing the quality of the final product. To this day, simulation is the most common approach to verify the behaviour of the system under development. But there is an inherent major drawback, the limitation to a finite number of test scenarios.

Formal verification techniques enable proving that a model is indeed compliant to its specification, even if case scenarios are infinite. Among them, model checking is able to perform verification on a computer in an automated process.

The use of model checking is already a common practice in some high-tech industrial areas such as aerospace, railways, microcomputers and more generally in the development of any critical embedded system, to guarantee an optimal reliability. Techniques and tools have evolved to overcome some original limitations of model checking and today it is possible to handle physical models with continuous and discrete parts. Known as hybrid model checking, this opens up new application perspectives, especially in the field of mechatronics.

In the current state of the art, hybrid model checkers are usually limited to proving safety properties (i.e. the system will never enter a certain set of states), because they often rely on over-approximation. This makes them good candidates to prove the correctness of airplane collision avoidance manoeuvres for instance.

[1]Extensible mark-up language used to define rules for encoding documents in a format which is both human-readable and machine-readable.

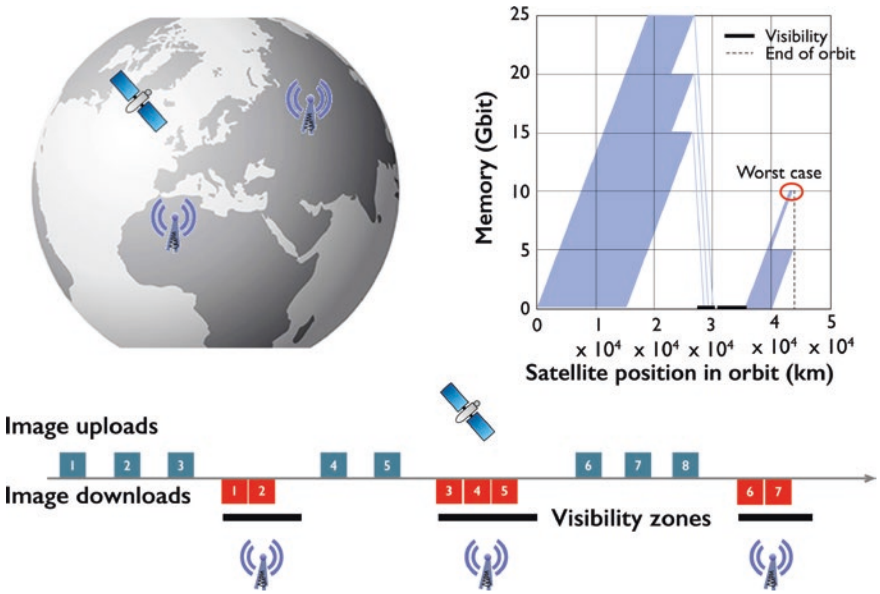

Fig. 3.3 Verification of a satellite memory using hybrid model checking

Figure 3.3 shows another case example, a satellite has the mission to capture Earth images upon request and download them to ground stations whenever they become visible; the goal is to formally verify that the memory buffer of the satellite will never be exceeded, based on a specific ground stations configuration and a maximal number of requests per orbit. The requests are discrete, whereas the data transfers are modelled continuously.

Hybrid model checkers differ from one another in their expressivity (e.g. which kinds of differential equations they support) and the over-approximation methods they provide.

When proving safety properties is not enough, hybrid theorem provers such as *KeYmaera* [37] can be used as another formal verification option in a mechatronic context. These try to automate the mathematical proof of the requested properties, but usually require some advanced inputs from the user along the demonstration in order to come to a conclusion, which may be very tricky for complex systems.

3.3.5 Ability to Optimize Test Campaigns

Sometimes the formal verification of a mechatronic system is not feasible, for instance because of complex modelling artefacts or scalability issues. Possible or not, test campaigns will still be needed once the product is built to check its conformity to the specification models and validate it against the requirements. In any case, the limitation to a finite number of test cases which can be executed (first in simulation, then in real life) makes it essential to identify the most relevant and representative ones.

The tendency is to generate optimal test cases automatically. Two main elements determine how this is done: first the test selection criterion, which defines what is driving the test case generation and second the test generation technology, which is the algorithm actually producing the results. Typical examples for both are given below [38].

Test selection criteria:

- Structural model coverage criteria—these exploit the structure of the model to select the test cases. They deal with coverage of the control-flow through the model, based on ideas from control-flow through code.
- Data coverage criteria—the idea is to split the data range into equivalence classes and select one representative from each class. This partitioning is usually complemented by the boundary value analysis, where the critical limits of the data ranges or boundaries determined by constraints are additionally selected.
- Requirements coverage criteria—these aim to cover all the informal system under test (SuT) requirements. Traceability of the SuT requirements to the system or test model/code can support the realization of this criterion. It is targeted by almost every test approach.
- Test case specifications—when the test engineer defines a test case specification in some formal notation, these can be used to determine which tests will be generated. It is explicitly decided which set of test objectives should be covered.
- Random and stochastic criteria—these are mostly applicable to environment models, because it is the environment that determines the usage patterns of the SuT. A typical approach is to use a Markov chain to specify the expected SuT usage profile. Another example is to use a statistical usage model in addition to the behavioural model of the SUT.
- Fault-based criteria—these rely on knowledge of typically occurring faults, often designed in the form of a fault model.

Test generation technology:

- Random generation—random generation of tests is done by sampling the input space of a system.
- Graph search algorithms—dedicated graph search algorithms include node or arc coverage algorithms such as the Chinese Postman algorithm,[2] which covers each arc at least once.

[2]Also known as the route inspection problem or postman's tour.

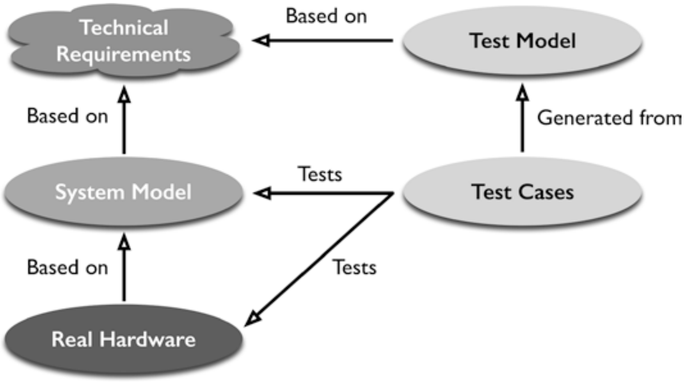

Fig. 3.4 Model-based testing using explicit test models (*top*) versus design/specification models (*bottom*)

- Model checking—model checking is a technology for verifying or falsifying properties of a system, but can be used to generate test cases based on the given counter examples.
- Symbolic execution—the idea of symbolic execution is to run an executable model not with single input values but with sets of input values instead. These are represented as constraints. With this practice, symbolic traces are generated. By instantiation of these traces with concrete values the test cases are derived.
- Theorem proving—usually theorem provers are used to check the satisfiability of formulas that directly occur in the models. Here it uses mathematical procedures to search through the possible execution paths of the model so as to find test cases and counter examples.
- Online/Offline generation technology—with online test generation, algorithms can react to the actual outputs of the SuT during the test execution. This idea is used for implementing the reactive tests also. Offline testing means that test cases are generated before they are run. A set of test cases is generated once and can be executed many times.

The most appropriate test generation technology often depends on the kind of source model to deal with. Some approaches create test cases from a test model, whereas other ones take design models as input, as shown in Fig. 3.4. Both can be behavioural models, but the first kind describes what the tester does to test the SuT (i.e. which stimulations he gives and verifications he makes), whereas the latter describes how the SuT is working. The point of view is thus different (tester versus implementer), as well as the objective (validation versus solution).

3.4 Challenges in Operation

3.4.1 Ability to Use Design Models to Improve Maintenance

Currently, there is little reuse of design models in the maintenance of aerospace systems. However, this knowledge about the behaviour of systems can be used to improve diagnosis, prognosis and maintenance planning.

In diagnosis, behavioural models can be used to correlate the observations made on the system and some failure modes or some degradation of the components. This permits the estimation of the current state of components (e.g. filter clogging) and the performance of maintenance operations in a more accurate and faster way since the root cause of a system failure might be detected without needing to inspect all its parts.

Similarly, prognosis activities try to predict the future state of the system in order to anticipate failures and plan preventive maintenance tasks. For instance, estimating the remaining useful life of a system by analysing the data transmitted by its sensors permits the planning of specific maintenance tasks (e.g. tank refill), to anticipate needed resources (spare parts) and adapt operations accordingly.

Technically, the use of models for diagnosis/prognosis generally requires state estimation techniques (e.g. linear regression, Kalman filters). These techniques permit to minimize the error between the observations on the real system and the model by playing on some parameters of the model (failure, degradations). Since several configurations of the model may match the observed behaviour, the definition of observed variables is the main driver for an efficient diagnosis.

In practice, embedding the model is not always possible because of required computational resources. However, the diagnosis/prognosis tasks can be done on ground in light of transmitted telemetry (offline PHM).

3.4.2 Ability to Use Design Models to Improve Control

Another use of design models to improve operations is in their use for the control of the system. Indeed, in some cases, there is an interest to use the knowledge contained in behavioural models in the control logic of the system. This is known as model predictive control (MPC). The use of MPC is particularly adapted if the system has slow dynamics (e.g. chemical plants) or if the control must consider a long-term usage of the system (e.g. plan resource usage for a mission).

An example of usage of MPC is for energy management. For instance, a simple model of a hybrid propulsion vehicle can be used in the power control algorithm to optimize the fuel burn and the use of batteries given a particular mission. This enables a significant increase in performance compared to a classical control algorithm. However, the certification of such intelligent algorithms is still a challenge.

Also, since embedded models are constrained by the real-time requirement, and since design models are generally not designed for such applications, a simplification of the models must be achieved. This simplification process introduces a trade-off between real-time performance and representativity of the model.

3.5 Conclusion

Some of the main challenges in the design of mechatronics system were exposed from an industrial viewpoint. The main driver for this evolution is the reduction of development costs and time as well as the improvement of the designed products in terms of cost and performances.

As can be seen, many of these challenges deal with the virtualization of the product to improve its design, its validation or its operations. Indeed, virtualization enables more flexibility in the different stages of the development at lower cost.

In design, the multiplicity of components and of specific domains of mechatronics systems requires seamless integration of FEM and system-level models during design. For this purpose future works can focus on dedicated metamodels for mechatronics sizing activities and easy assembly of models thanks to graph-based MDO approach.

In V&V, future work should focus on the formal verification of mechatronic systems since it would considerably lower the costs of certification.

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Chapter 4
TiV-Model—An Attempt at Breaching the Industry Adoption Barrier for New Complex System Design Methodologies

Craig Melville, Xiu-Tian Yan and Lixiang Gu

4.1 Introduction

System design and engineering is fundamental to the creation of the devices and technologies that have become a large part of our lives. Technology companies, motor vehicle manufacturers and inventors go through this process to develop all kinds of luxuries and necessities for everyday life in the twenty-first century.

Often from the perspective of the user, the means as to how their products were created is not of concern; it works so it does not matter. To the designer, the methods and methodologies are very important tools in their belt, but some tools are better suited to the job than others. Current methodologies, such as the Mechatronic V-Model, provide decision-making knowledge and support to designers and enable simple platforms as the basis for development.

This information source is important, and it tells the designer what it is that needs to be known, a crucial component of the process for engineers, especially when designing complex systems. Research finds novice designers to be only aware of 35 % of their knowledge needs in the aerospace industry [1], showing that there is a very high competency barrier associated with complex systems.

This high competency standard is but one of the many difficulties that arise from complex system design relative to conventional system design, but there are many more, and researchers and companies will always be interested in looking for new ways to do things. The interest in developing more efficient and effective methodologies for the design of complex systems can thus be argued for on economic terms alone.

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Take for instance the example of BAE Systems, one of the world's biggest and most successful developers of complex systems in the form of naval, aerospace and ground platforms for various functions. With £1.3 billion in revenue in 2014 [2], a small investment in research into the design process improvement even for tiny reoccurring percentile gains would be a simple choice. Academia is one environment in which to study the application of new methods and methodologies, but as Birkhofer et al. [3] show in their work, methodologies born of academic research are rarely or reluctantly adopted into practice. The reasons for existence of these adoption barriers range from the lack of perceived usefulness, bad communication of concepts and absence of "*proof of usefulness*".

This chapter will introduce the TiV-Model, a design methodology for complex system projects that aims to put to rest concerns facing the adoption of the methodology into practice. The next section will contain a description of the TiV-Model, how it was developed and will show how it plans on solving design related issues. This will be followed by the validation planning of the methodology and future plans for development concerning predicted future challenges within the industry.

4.1.1 Complex System Design

To understand the difficulties in Complex Systems Engineering (CSE), it is necessary first to distinguish between regular systems engineering and CSE. Traditionally, engineering design is considered to be an iterative design process "*concerned with the creation of systems, devices and processes useful to, and sought by, society*." [4]. In short and in a way, CSE is concerned with the investigation of the means to the creation of complex mechatronic systems such as robotic systems. The most common understanding of this is the engineering design process, a general term used to express the series of steps involved in the design of systems. Figure 4.1 shows the design engineering process in simple form.

Design methodologies and the engineering design processes are, for the most part, interchangeable. Most methodologies have some focal point such as an optimised critical path, DfX[1] methods or some other element that provides for more favourable results in certain areas relative to other methodologies. A core difference between complex and conventional methodologies, and also a key identifier of the former, is that conventional projects try to balance out manufacturability and repeatability with the product quality. Complex projects in contrast tend to spare no effort in achieving their goal, even with the use of expensive or difficult manufacturing processes, particularly where the design is a one-off.

[1]Design for X.

Fig. 4.1 Engineering design process (after [5])

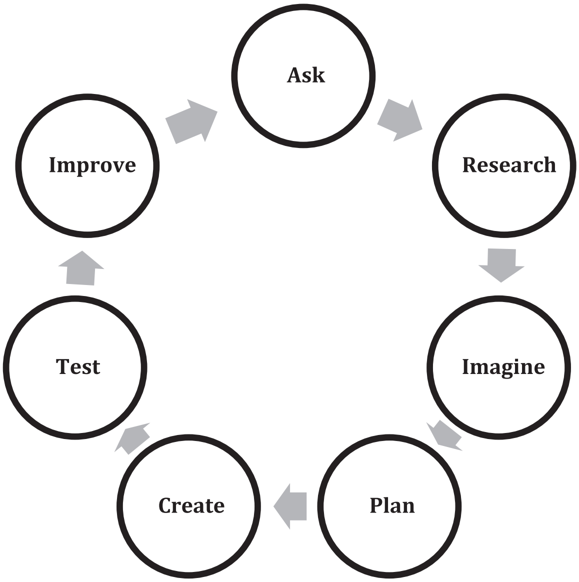

Table 4.1 Conventional, mechatronic and complex projects [6]

	Conventional	Mechatronic	Complex
Volume production	High/Very high	High-very low	Low/Once
Cost per unit	Low/Very low	Moderate/High	High/Very high
Project size	Small/Medium	Medium/Large	Large/Very large
Average quality	Low/Very low	High	Very high
Focus	Manufacturing	Product	Project
Manufacturing style	Highly automated	Automated/Repetitive	Mostly manual
Project management	Linear methods	Linear methods	Non-linear methods

4.1.2 Complex Versus Conventional System Design

The engineering of complex systems comes with additional challenges that need to be accounted for in the engineering design process. A majority of these differences stem from the increased scale and complexity of the project. Issues such as an increased number of parts and manufacturing operations due to the design's physical size can be easily accommodated. Processes related differences due to budgetary and time constraints, such as the reduced accessibility of physical prototyping, will have to be explicitly addressed and made aware to the designer. Table 4.1 sets out some of the qualitative properties of conventional products, mechatronic products and complex projects.

Table 4.1 serves to highlight some of the core issues surrounding the completion of complex projects, namely.

Complex Design Management—The data and physical output of large scale CSE projects can be overwhelming when compared to traditional systems engineering. Large capacity servers are required to manage the amount of data, but the data itself is more varied. For example, a CAD model of a satellite design may contain separate models of the electronics, chassis, fixtures, mechanisms and heating elements, possibly further divided by subsystem or payload. This added layer of complexity must be accounted for in the methodology and the management system. The sheer volume of files must be tracked and accounted for as well as appropriately labelled for use in a group environment.

Complex Knowledge Base—Complex systems are multidisciplinary in nature and require a firmer grasp of the required knowledge bases. Tolerances are smaller, requirements more demanding and designs more convoluted than for regular mechatronic engineering. Documenting and tracking this knowledge is more important and computer aided tools are essentially mandatory to ensure each team is up to date with the huge amount of information, such as operating principles and design specifications. This wider range and expertise of knowledge means that specialist teams will be more common; allocating these to areas of the project that need them is an additional planning complication.

Increased Uncertainty and Risk—As with any high budget project, the more money invested into it, the more money is wasted on failure. The increased complexity, in the form of increased points of failure, tighter tolerances and non-standard design practices also brings additional uncertainty in both process and design. Hiring new graduates and novice engineers may be perceived by management as detrimental to the project as experienced engineers are expected to take the lead and perform a disproportionate amount of the work. Design teams require more information, skill and agency to complete the tasks relative to that of conventional systems engineering.

Design Evaluation and Non-Destructive Testing—High budget projects generally have the freedom, and are encouraged to develop working prototypes to test and validate the "*real-world*" behaviour of their design. In large scale CSE projects, the nature of the design solution is, however, often one that cannot be wholly prototyped as cost, time and resource constraints prevent this. In a best case scenario, subsystems or components can be prototyped, but not full systems. If full systems are to be tested, it would be in the post-fabrication stages, thus non-destructive testing is the only way to preserve the system integrity. Reliance on simulation and on-paper calculations can be considered mandatory otherwise.

4.1.3 Methodology Adoption Resistance

Badke-Schaub et al. [7] summarise the perceived issues with new design methods and methodologies. Figure 4.2 then shows the common industry reasoning for the lack of integration of new design models and methods.

Performance issues relate to the absence or uncertainty of proof that the methodology will work as intended or produce results. This stems from a lack of validation on the part of the creator or of follow-up case studies. The presentation of

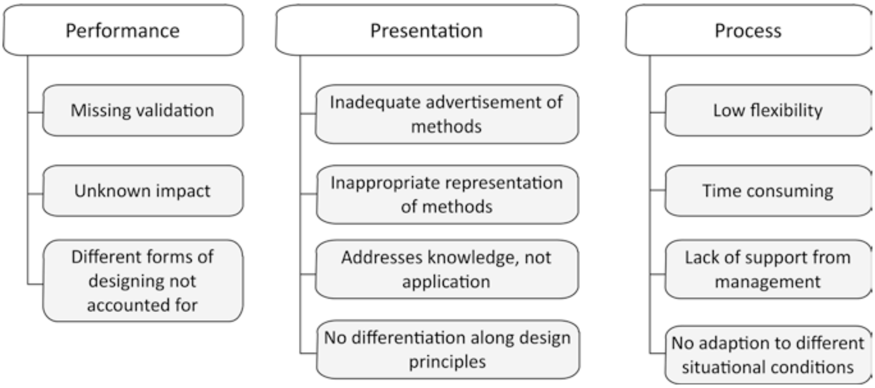

Fig. 4.2 Industry perspective barriers to methodology adoption

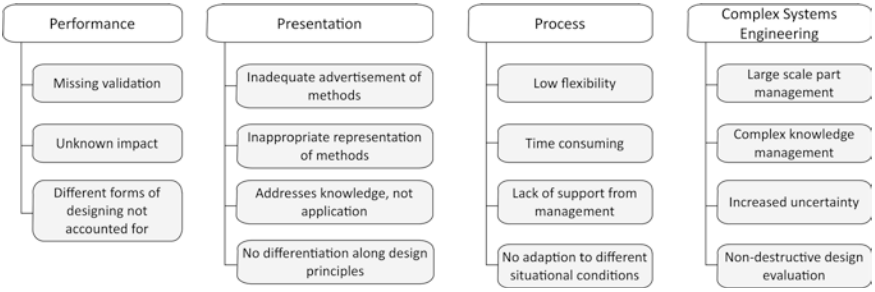

Fig. 4.3 Comprehensive issue matrix for CSE methodology adoption

the methodology refers to the effective communication of information and its clarity. Process relative issues often involve the intra-task efficiency of the model, for instance the trade-off of time/cost/flexibility.

If the issues from the CSE perspective are combined with the adoption barriers list, it is possible to effectively create an issue matrix specific to design methodologies within complex system engineering industries by adding an extra column to Fig. 4.2 as in Fig. 4.3.

The matrix of Fig. 4.3 then provides a list of problems that can be solved at the methodology level and it is to address the TiV-Model that has been created, a CSE design model that aims for industry adoption by focusing on the issues that commonly prevent industry adoption as well as the issues faced by CSE designers.

4.2 TiV-Model

The TiV-Model of Fig. 4.4 is a CSE design methodology that possesses multiple traits that make it highly beneficial for use in the complex systems industries with

	System Models	Tasks	MA Models	Knowledge Database
Investigative	**Design clarification** Trigger/Customer need Research information Rough specification document Cost analysis	Needs analysis Create specifications		**D1** Mechatronics working principles Mechanics Circuitry
Legislative	**Space legislation** Contract Technology limits Legalities Mission launch requirements Qualitative specification document	Conceptualise design specifications		**D2** Space environment Launch environment
Qualitative	**Conceptual Models** Mechanical/Electrical concepts Data topography/control Functional concepts Weighting criteria Final qualitative concept	Concept generation Weighting criteria Concept evaluation	**Approximate MA Models** Requirements for MA system General idea of MA technology Rough materials plan	**D3** Mission requirements Tools and objectives
Quantitative	**Embodiment Models** Solution model Circuit model Control logic model Aesthetic model Functional model	Detail design Control design Final concept	**Embodiment MA Modles** Embodiment models with manufacturing process Material properties	**D4** Regulations Laws Legislation Political implications
Evaluative	**Mechatronic System Models** Dynamic evaluation model Kinematic analysis model Geometric model FEA model	Multi-perspective modelling Simulation modelling Prototyping	**Logistic Models** MA simulations model Costing model Tooling model	**D5** Engineering design principles CAD Conceptual design Embodiment
Productive	**BoL Phase Models** Finalised inclusive model Installation model	Manufacturing Assembly Pre-launch test Launch rig assembly	**Fabrication Models** MA machining model Launch platform model Lifespan model	**D6** Component database Standard components Materials database
Operative	**Operational/EoL Models** Control model Disposal model Real-time function model Haptic feedback model	Launch Operation Disposal	**Maintenance Models** Maintenance/servicing model Inspection model	**D7** Simulation block database Programming language

Fig. 4.4 The TiV-model

a focus on spacecraft and satellite development. The development focused on taking an existing model platform and adjusting certain characteristics.

Categorised Sequential Task Process—By categorising tasks into stages as a sequential process, much like traditional design processes, the process can be simplified into a step-by-step programme of tasks. At a glance one would think that this hinders the application of concurrent engineering. However, by using knowledge databases, the general stage tasks can be partitioned into discipline specific tasks and goals. This will allow either a traditional approach to the design process, or the more modern concurrent approach depending on the preference of the organisation or team. Allowing for both of these approaches ensures the general flexibility of the model.

Goal Oriented Process—Traditional design methodologies will sometimes incorporate specific methods as part of the design process; having methods that are well proven to work for that specific application can be beneficial, but ultimately means that the overall flexibility of the methodology is compromised. Additionally, by focusing on the task rather than the short term goal, new designers may not understand the purpose of doing such a task, leading to a possible chance of failure. The TiV-Model instead states which deliverables are required at that stage, while providing possible, but not definite, methods to accomplish the task.

This allows organisations to adopt the model without changing their pre-implemented methods or tools. This also eliminates the risk of the design team performing a task simply for the sake of performing a task, which can occur if leaders do not specify the "*Why*?" behind it. By focusing on what is needed of them as an end result, designers can understand the process, focus on the output and are still free to use whichever method preferable to obtain that output. Again, this flexibility maintains the value of the methodology across industries and applications.

Idealised Requirements for Accurate, Non-Destructive Validation of Design—Typically, the prototyping stage in system design would be used to validate specific functions or systems, the cost/time/resource constraints of CSE make this form of validation much more inaccessible. The reliance on computer aided means of validation can, however, be accommodated in the methodology by ensuring that multiple system and manufacturing/assembly models are created.

Discipline specific models to evaluate parameters such as thermal properties, yield, kinematics and geometric interferences will be integrated into multifaceted models, designed to simulate the actual environmental and loading conditions of the model. For example, launch resonance conditions and the effect of rocket shroud heating can be modelled independently, but running both of these aspects together will ultimately give a more reliable result. Combine this with iterative retroactive "*reality checks*" for the simulation data, and the need for prototyping and destructive testing can be effectively reduced.

Simplified Resource Allocation Recommendations—For certain stages of the design process, teams will be formed in some capacity, either functional or disciplinary. The project planners then have to allocate these teams to tasks pertaining to their expertise. Specialists may also be required for temporary contracting depending on the variety of the in-house design team. To plan for situations like these, the specialist knowledge types have been categorised into databases and linked to the stages where this expertise would be required. In doing so, the project planned can look ahead at the kind of disciplines required for the project and hire ahead of time, reducing cost and time.

Communicable and Understandable Language and Processes—One of the most crucial aspects of the methodology is its ability to be easily understood, time spent educating team members does not directly add value to the project, so as little as possible is the ideal. A framework that is easy and quick to learn will be welcomed by novice and experienced designers alike, as it enables the newer designers to pick up the slack earlier in the project without being carried by experienced designers.

The "Tiv" component in the model name enables a simple memory trigger to remember the stage names and general contents at will (QualitaTive, LegislaTive, etc.). A simple memory game like this can help boost first time retention of model concepts. By segmenting the tasks, deliverables and databases into a neat column-row dichotomy it is hoped that the model can retain a visual appearance that aids recognition of elements and understanding of task/goal flow.

4.2.1 Model Description

The TiV-Model has the essential steps required for any design process, each of these are labelled with a memorable name pertaining to nature of the stage. Tables 4.2 and 4.3 then show the type of information being presented.

Performance—The core problems associated with adoption from this perspective is the lack of study into validation of the methodology and "*proven*" usefulness. The TiV-Model will be built on the provable performance and is currently

Table 4.2 TiV-Model stage descriptions

Stage	Description
Investigative	User needs, market research, technology research, specification generation
Legislative	Planning, mission statement finalisation, contract agreement, qualitative spec. document
Qualitative	Initial design proposals, mechanical/electrical/control concepts, general solution proposals, ballpark costing
Quantitative	COTS component specifications, detailed design, subsystem design, costing, custom part design, data scanning for 3-D reconstruction of manufactured parts
Evaluative	Prototyping, simulation of launch, system performance and manufacturing facility, final solution decisions, meshing and model reconstruction based on scanned data
Productive	Part creation/buy-in, subsystem assembly and testing, system assembly and testing, system modifications and tweet based on reconstructed models from scanned data
Operative	Launch, operation, control, maintenance, repair based on 3-D scanned data, inspection, and disposal

Table 4.3 TiV-model column descriptions

Column	Description
System models	These are the models that represent the system through CAD, concept and detail design, including core outputs
Tasks	The core methodology, followed by the designers, shows interactive processes and critical path
Manufacturing/Assembly models	Models that relate to the state of manufacturing or assembly, these are important for outsourced jobs and production planning
Knowledge database	Indication of what types of knowledge is needed and at what point during the project. Makes resource allocation and planning easier

undergoing the verification and validation process. By performing necessary validation of the methodology through verifiable means and by performing post experiment case studies on the implementation of the methodology, empirical data can be given to prove the validity and performance of the TiV-Model.

Presentation—Successful communication of a model's core principles involves considering the designer's point of view during the model's development. TiV-Model was initially designed with ease-of-use from a designer's perspective in mind. Many of the changes from the base version of this model, the 3-column model, have involved redefining task and timeline taxonomy to "*clean up*" the presentable information on the core methodology view [8].

The organisation of presentable information involved;

- Refining the concept of system models as deliverables representative of the system overall.
- Refining the concept of Manufacturing/Assembly models as deliverables that represent the details required for buy-in, manufacturing and assembly of components.
- Showing the critical task path and the key deliverables for that stage of the process.
- Splitting the middle stages of the methodology (Qualitative-Evaluative) by design discipline and showing rough critical path for each.
- Identifying knowledge databases by discipline.
- Displaying when particular knowledge is needed at which stage.
- Displaying key deliverables with suggested methods, maintaining the option for alternative methods.

The information displayed on the TiV-Model allows the designer to make a quick and accurate extrapolation of the meaning behind the visuals and the wording. Methods are "*advertised*" and encouraged, but ultimately subject to change depending on the approach of the designer or organisation. This flexibility is communicated by showing that the task is outcome oriented, with methods paths only suggested and not enforced. Designers with the most basic systems engineering knowledge can develop an understanding of the process and a natural experiment that shows this will be discussed.

Knowledge base taxonomy is divided into general disciplines that are shown in the model as well as where they are best applied. This ensures planners recognise where knowledge is to be applied within the project.

Process—The process issues were addressed through changes made by logical reasoning, the effectiveness will be demonstrated in the experiment referred to above and discussed later. As already mentioned, flexibility is ensured by goal orienting the tasks, leaving the method open to the organisation's preference, yet offering options and suggestions for placeholder methods. This aids new designers in making decisions that would otherwise require more information or expertise. Support from management is an extension of how well integrated the methodology is from bottom-to-top in the organisation. However, the success of integration is subject to acceptance at both management and user level. Direct benefits to management of the project would come from the interactive program planned for the final development stage of the TiV-Model.

Complex Systems Engineering—With the increased uncertainty associated with CSE, measures taken in the methodology can offset this. As mentioned before, by presenting suggestions for methods and clarifying where specific knowledge should be used, the uncertainty can be minimised and thus the project risk associated with that uncertainty reduced. Solving the problem of a high part and file count for a CSE project would be the responsibility of the management system in place and this is addressed as an interactive component of the methodology.

Additionally, the entry skill barrier to new engineers can be reduced by recognising the knowledge gap between them and more experienced engineers, what knowledge they need and when. TiV-Model, while being goal oriented, makes suggestions for possible methods to use to accomplish the task. These methods are optional, and organisations with prior operating principles can implement their own methods, but in the absence of that knowledge the designer has the capacity to retain their agency.

4.2.2 Potential Benefits

Designer

- Easy to use and understand current tasks.
- Information needed is provided at the time it is needed.
- Transparency in planning allows greater agency and communication.
- Novice engineers enabled to contribute more.
- Experienced engineers not relied upon too heavily.
- Choice of method, tools and style dependant on designer or organisation.

Project

- Computer-aided validation focus has higher chance of ensuring correctness first time.
- Concurrent design options may help improve systems integration quality.

- Clear deliverables helps improve error checking and identifying points of failure.
- Documentation of each stage is part of deliverables required, meaning retroactive checking and changes can be made during the project.
- More means for design validation.

Planning and Management

- Stage and task breakdown is categorised to ease timescale planning and rough resource allocation.
- Sequential tasks broke down by discipline, allowing for either a traditional or concurrent engineering approach.
- Knowledge requirements for each stage outlined, allowing plans for specialist help.
- Planning is transparent and thus easily communicable.

Organisational

- Flexible goal-oriented design means tools and methods need not change.
- Keeping tools and methods means very quick and easy implementation into organisation.
- Reduce costs by;
  - Supporting inexperienced engineers.
  - Using computer-aided design validation as opposed to prototypes.
  - Retaining in-house tools and methods.

Industry

- Methodology validation breaks down industry barriers for academic model acceptance.
- Stepping stone example for new, improved design methodologies.
- Hiring of inexperienced engineers will be justifiable, as risk is reduced.
- Non-destructive and computer-aided means of design validation could reduce project costs across all projects.
- Flexible and modular methodology sections means TiV-Model can be adopted into any CSE industry, a potential for a standard.

4.3 Methodology Validation

In order for a new methodology to be accepted as a working, feasible alternative, it must first be scientifically verified and validated. Verification of design methodologies involves confirming that the internal logic of the methodology is consistent, validation involves proving that the methodology will provide the desired output effectively and efficiently.

4.3.1 Validation Methods

In the realm of engineering design methodologies, research into the validation of models is somewhat rare. Three suitable models were considered for use in the validation of TiV-Model.

Technology Acceptance Model (TAM)—The TAM was introduced as a means of validating tools, models and methods from a usability perspective. The model was designed specifically for the validation of computer systems, but can be expanded for general use. The TAM focuses on the acceptance of a model by measurement of the users intentions; perception of use quantifies validity in this sense [9].

Method Evaluation Model (MEM)—MEM is a method that focuses on the validation of design models and methods for information systems [10]. Validation is comparable in many ways to TAM, however, the focus was on validation by user perception in order to obtain projected performance estimates. However, due to the limited case study evidence supporting this model's success, and the need for a more solid evaluation structure, this model was not selected.

Validation Square—The method that was ultimately chosen to validate the TiV-Model's experimental data was the Validation Square [11]. This is a model used specifically to demonstrate the validity of design methods by scrutinising the method in four key areas, as shown in Fig. 4.5.

The Validation Square was picked due to its suitability to the field; it was created for the purpose of evaluating design methods, the conditions for validation are far more stringent than the other listed models and the Validation square also goes as far as to validate itself. The model uses both the theory behind the method and the empirical data achieved from experiments to verify the method's structure and validate its performance. The validation is achieved by challenging the methodology with six logical statements that must be proven true.

1. The individual constructs of the method(ology) are valid.
2. The method(ology) construct is internally consistent.
3. The example problems are relevant to the method(ology).
4. The method(ology) is useful to the example problems.

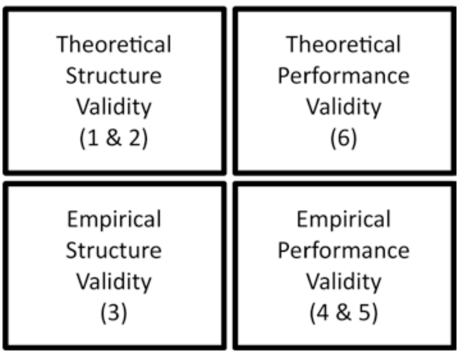

Fig. 4.5 Validation square

5. The usefulness is a result of applying the method(ology).
6. The method(ology) is useful beyond the example problems.

These six statements have been proposed to be proven true across three experiments. Statements 1–3 can be demonstrated in an uncontrolled natural experiment, showing that the methodology is designed to be used in the systems engineering context. Statements 4 and 5 can be shown in a controlled group experiment designed to prove the usefulness of the methodology compared with other successful design methodologies. The sixth and final statement is justified in the Validation Square as a "*leap of faith*" once the other five statements have been proven true; the methodology is as good as valid. However, the project aims to go one step further and use the TiV-Model in an actual CSE scenario, upon which a case study will be built to prove the methodology's effectiveness.

4.3.2 Experiment 1—Natural Experiment

The natural experiment is a means of showing that the TiV-Model is capable of the core function of producing a complex design solution as part of a mechatronic design project. This will be the first soft implementation of the methodology in a realistic use environment with the purpose of obtaining usage data from the respondent. The experiment is rather simple; a fourth year design engineering student was tasked with the design of a robotic solution for the automated application of icing on cakes, this involved a focus on the design of the mechanism but also included the control and electronics at a conceptual level. Post-project feedback is obtained from the respondent in the form of a qualitative feedback survey, followed up by an informal feedback session, where efforts will be made to obtain suggestions to improve suitability for CSE and usability of the model.

4.3.3 Experiment 2—Controlled Comparative Study

The second experiment aims to prove the 4th and 5th statements of the Validation square. The methodology can be proved to be useful to the example problems by comparing "*usefulness*" of the TiV-Model to that of existing successful models. Some questions for this approach are:

- What variables constitute usefulness in a design context?
- What successful methodologies are valid for comparison?
- How can an experiment be designed to extract these variables?

While the specifics of which methodologies to use are being planned, it is likely the experiment which will take the form of previously published comparative studies. In a previous study focused on comparing the V-Model with other life cycle development tools, comparison extends no further than the literature and logic [12]. In the experiment it is aimed to demonstrate the hypothesis of these comparisons via controlled environment, where teams of designers will each be using one of three design methodologies in a performance incentivised CSE project. Effectiveness will involve the comparison of output design qualities and efficiency will, much like the natural experiment, focus on qualitative feedback from the designers as users.

To understand effectiveness there needs to be measurable variables generated by the project that can be compared. The TiV-Model's ideal competency is that it is thoroughly validated, so efforts were made to understand the testing parameters of arguably the most rigorously tested field of all; medicine.

Validation Lessons from Medicine—When it comes to experiment design and testing standards, few organisations are more stringent than those involved in medicine. This is perhaps due to the nature and risk associated with the development of pharmaceuticals. There may be no testing standards for experiments with design methodologies, but methodologies used in medicine can be a useful equivalent benchmark. Frey and Dym [13] discuss in great depth how medicine can be taken as a useful analogy towards the validation of design methods. Analytical methods for laboratories have to follow set standards such as those of the US Food and Drug Administration (USFDA), Current Good Manufacturing Practice (cGMP) and ISO/IEC in order for their methods to be eligible for validation. The standards include parameters that can be tested that reflect the success of the end product. These variables are;

• Accuracy	• Precision
• Specificity	• Limit of detection
• Limit of quantisation	• Linearity and range
• Ruggedness	• Robustness

By setting an acceptable threshold for these quantifiable values, medical researchers can determine effective "*success*" of a treatment or drug and compare it to other solutions. Design research can learn from this as many of these factors have equivalents in a design context.

The specifics of such comparisons are still up for debate, but on a "*closest match*" standard. The relevant factors can be determined for the evaluation of design solutions as opposed to medical ones. Table 4.4 provides the context for this evaluation in the medical domain.

Table 4.4 Relevant success measures in medicine compared to design

Test element	Design context
Accuracy	Satisfy design requirements
Precision	Repeatedly satisfy design requirements
Specificity	Ability to detect failures
Limit of detection	Largest acceptable "failures"
Linearity and range	Closeness in solution quality
Ruggedness	Design "effectiveness"
Robustness	Design "quality"

With these new parameters that determine success, based off equivalents in medicine, it is possible to continue with designing an experiment that will extract these parameters and enable the evaluation of the methodology to take place.

4.3.4 Experiment 3—Case Study

To prove the sixth statement, and determine that the methodology is indeed fit for practical use, a CSE project will be undertaken using the TiV-Model as the methodology of choice. This project will involve the design of a multifunctional mechatronic gripper for fixture on board spacecraft and structures. This is sufficiently within the intended design area of the methodology as a complex mechatronic project, demonstrating its original focus. This project will be documented and examined as a case study, evaluating the success or failure of the project based on similar measurable variables as the second experiment. If the project is successful, the validation will be complete and presentable as proven fact, more than most academic models can claim.

4.4 Next Steps and Conclusions

4.4.1 Interactive Software Integration

Relating to the goals of increased user-friendliness, the capacity to manage large scale projects and integrate with an organisation from top-to-bottom, the TiV-Model will be further developed into a comprehensive methodology and life cycle management system. By doing so, it is possible to effectively tie methods together with their respective tools, for example; evaluation of concepts by weighted convergence matrix is meta-linked to a dynamic group shared file that contains a House of Quality style matrix. This goal is very much inspired by the PLM systems developed by companies such as AutoDesk, and in heavy use by the likes of BAE Systems.

4.4.2 Closing Remarks

TiV-Model is a proposed solution to the question often asked in design research; "*why are new models slow to come to practical adoption*?" It can be shown that there are various concerns expressed by industry about the suitability of new models as well as their performance and usability. The key issue, however, is the lack of proven effectiveness or validation of said methodologies. By ensuring TiV-Model is thoroughly valid, it can act as an example of breaking down the barrier of acceptance to industry. It also aims to hold its own as a user-friendly and flexible alternative for the CSE industry. Validation of the TiV-Model will use the Validation Square, a suitably stringent means for design method evaluation, to prove that it can perform well. This validation process will encompass three experimental steps that mirror the nature of practical use more with each step. By showing TiV-Model can succeed and even thrive in similar projects, it is possible to remove many of the doubts industry may have about this new academically rooted model. It also works to satisfy future needs; the need for an overarching set of tools, methods and methodologies that encompasses CSE is predicted [14]. The TiV-Model will work towards the goal of a universally compatible architecture to accommodate new design methods and tools. Alternatively, by providing a verified and validated foundation, future method development can springboard from TiV-Model, perhaps even merging as a powerful supplement to the methodology.

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Chapter 5
Digital Twin—The Simulation Aspect

Stefan Boschert and Roland Rosen

5.1 Overview

The vision of the *Digital Twin* itself refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all—the current and subsequent—lifecycle phases. In this chapter we focus on the simulation aspects of the *Digital Twin*. Today, modelling and simulation is a standard process in system development, e.g. to support design tasks or to validate system properties. During operation and for service first simulation-based solutions are realized for optimized operations and failure prediction. In this sense, simulation merges the physical and virtual world in all life cycle phases. Current practice already enables the users (designer, SW/HW developers, test engineers, operators, maintenance personnel, etc) to master the complexity of mechatronic systems.

Nevertheless, the technical challenges are further increasing. Software and especially network connectivity extend the functionality of mechatronic systems. As the traditional mechatronic disciplines (mechanics, electric and electronics) are realized in a more integrated way, their interfaces will be more intertwined. To design these systems and to validate properties by virtual tests in early phases as well as operation and service support multi-domain and multi-level simulation approaches are necessary. These approaches must be embedded in the system engineering and development process and reused in all following lifecycle phases.

In the two dimensions of time and level of detail a seamless *Digital Twin* is required, which focuses on the following points:

- Reducing time-to-market is today, and will remain so into the future, a key aspect. The intertwining of simulation models over different levels of detail, over all involved disciplines and over lifecycle phases must be enforced.

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- The *Digital Twin* should be designed in its principal structure in advance and needs its own architecture. It extends the pure data which is available in design and engineering, and is collected during operation and service by simulation models. These simulation models describe and make available system behaviour, performance evaluations and quality considerations. The *Digital Twin* provides an interface to different models and data in different granularities and keeps them consistent.
- Optimization of mechatronic products and systems during their use or operation, e.g. as an element of production equipment or supply part, will be more important. The gap between development and operation must be bridged. The redevelopment of models for operation and service is time-consuming and cost-intensive.
- The *Digital Twin* connects different value chains. For example, a *Digital Twin* of a product which is used as production equipment in a production system transports important information (data and executable models) to producers and manufacturers, e.g. for an easier system integration (virtual commissioning, production planning, etc.). This requires that the *Digital Twin* contains models with different granularity and needs in general a predefinition of its principal architecture (structure, content and purposes). The *Digital Twin* is not a data monster, which includes everything from all lifecycle phases.

We show in this chapter that simulation has the potential to be integrated into all phases of system design in the future. As such it will be available as an additional feature during all operation phases. As more and more features are realized using software instead of hardware, simulation models are needed to describe all disciplines—separately and in combination—and on different levels of detail. In total, only simulation methods will master the extended challenges coming from new technologies used in all kind of technical systems.

5.2 The Waves of Simulation in System Development

In the last decades, simulation has developed from a technology largely restricted to computer experts and mathematicians to a standard tool used daily by engineers to answer manifold design and engineering questions, as suggested in Fig. 5.1.

In the 1960s–1970s numerical algorithms, generally implemented in FORTRAN, were used to calculate specific physical phenomena to solve design problems. However, this was limited to very special cases, as there would have been few simulation experts. With the increasing spread of workstations and personal computers the number of users grew rapidly and the provision of simulation tools for repetitive tasks like control unit design began to be established.

With a higher number of simulation users, the economic growth of tool providers, technical improvements like increased computing power simulation of all involved disciplines and on different level of detail was possible. Today,

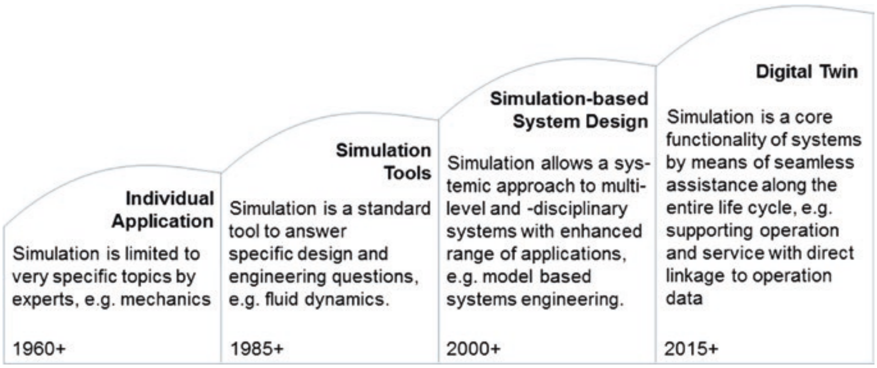

Fig. 5.1 The *Digital Twin* is the next wave in simulation technology

simulation is the basis for design decisions, validation and testing not only for components but also for complete systems in nearly all application fields. This trend is unbroken and will be continued in the next years.

Simulation models for all aspects can be implemented and will be provided in parallel with the real component, product or system, and of course, its use does not stop with the commissioning phase. It will be used, for example, during operation for optimized operations and during service for lifetime calculation and improved maintenance.

Other indicators also suggest that the golden time of simulation has just begun. This can be seen from a look to the evolution of mechatronic systems. In the preliminary note from VDI[1] [1] released in 2004, one can find a description of mechatronics as:

> Innovative products require an interdisciplinary combination of mechanical engineering, electrical engineering and information technology. The term 'mechatronics' is the expression of this

In the last 15 years, the nature of components, products and systems has changed. In particular, they offer a highly increased number of functions. This functional extension is realized by a larger number of parts and especially by a combined use of different disciplines. Beside mechanics, (or more generally physics) and electricity, the relevance of software and communication, e.g. intra- and internet connection, is raised. This leads to an increase of complexity and so to a stronger use of discipline over spanning methods—simulation is a powerful one. This trend will hold in the future.

Many products which were called "*electro-mechanics*" some years ago have evolved to mechatronic products. A very prominent example is a coffee machine which developed from a simple device for heating water to a fully automatic

[1]Verein Deutscher Ingenieure (Association of German Engineers).

device with programs for different coffee taste and advanced cleaning processes. In examples like this, the following three phenomena can be observed:

- Additional functions are offered by the mechatronic product which are realized more and more by software.
- The number of parts like drives or sensors in components, products and systems is increased.
- Intensive use of a combination of different disciplines. Software controls via actuators and sensors the physical section. In many cases the software is executed on microcontrollers which are located nearby and not on separated computer units.

These trends will continue, because there are simply no indicators that point to a change. Quite the contrary, in the near future two other trends will enforce the current development:

- Components to systems[2]—Mechatronic products gain a hierarchical structure or will be added as '*elements*' to larger systems.[3]
- Enforced connectivity[4]—Such as web technology, internet protocols and increased computing power in the product or system itself.

Taking a more detailed look into the communication capabilities of future mechatronic systems, Fig. 5.2 shows the enhanced understanding of mechatronic systems supplemented by open network capabilities compared with the VDI representation [1]. This principle structure was elaborated in the German Industrie 4.0 BMBF project mecPro[2] [2]. In this project the term cybertronic[5] is used to emphasize the importance of cyber capabilities for next generation mechatronic systems. Cybertronic was used as a shorter form for cyber-mechatronic to underline that the consideration of the physical system remains relevant for the complete system functionality. This all illustrates that the significance of simulation as a method to master complexity and to bridge disciplines will further increase.

On the one hand, the requirements for development of future mechatronic systems are rising, and on the other hand, the evolutionary development of simulation techniques leads to significant improvement in mastering the complexity during the design and operation phases. Nowadays in the industrial sector and in technical companies, simulation is still mostly considered to be a tool for research and development (R&D) departments. In addition to more traditional calculations, for instance in multiphysics simulation, aspects like "*communication by simulation*" and "*virtual experience*" are emerging applications in various phases of the

[2]Clarification of terminology—The authors are aware, and readers should be aware, of differing views and use of terms like elements, systems, products and components.

[3]This corresponds also to '*system of systems*' perspectives.

[4]Many terms are used to express this trend, e.g. Cyber-physical Systems, Internet of Things, Web of Systems, Industrial Internet.

[5]The term cyber-physical is more popular, but brings a different understanding of how the physical basis system is associated.

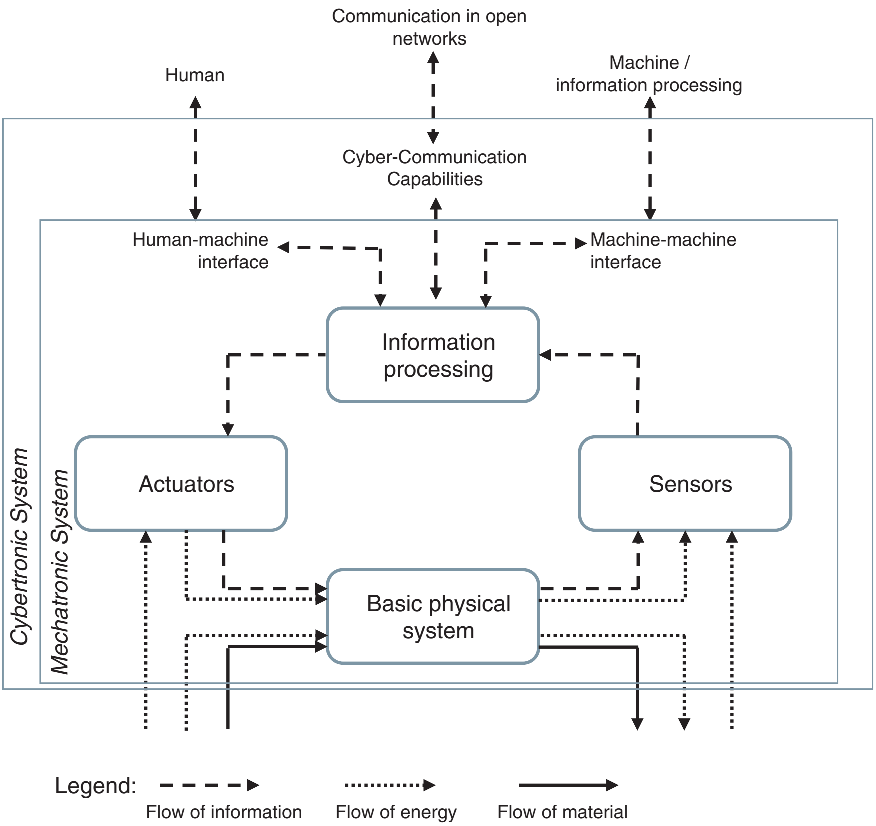

Fig. 5.2 Enhanced understanding of mechatronic system, as elaborated in the German Industrie 4.0 BMBF project mecPro^2 [2]

development processes. Extending simulation to later life cycle phases as a core product/system functionality, e.g. delivered before the real product itself or supporting the operation by simulation-driven assistance, is the next big trend in simulation [3]. Therefore, the realization of a "*Digital Twin*" is the key vision for industrial application. It includes simplified modelling processes, easy use of simulation, simulation workflows and seamless simulation along all life cycle phases including operation support.

5.3 Concept of Twins

The concept of using "*twins*" dates back to NASA's *Apollo* program, where at least two identical space vehicles were built, allowing the engineers to mirror the conditions of the space vehicle during the mission, the vehicle remaining on earth being called the twin. The twin was also used extensively for training during flight preparations. During the flight mission it was used to simulate alternatives on the Earth-based model, where available flight data were used to mirror the flight conditions as well as possible, and thus assist the astronauts in orbit in critical situations. In this sense every kind of prototype which is used to mirror the real operating conditions for simulation of the real-time behaviour, can be seen as a twin.

Another well known example of a "*hardware*" twin is the "*Iron Bird*", a ground-based engineering tool used in aircraft industries to incorporate, optimize and validate vital aircraft systems [4]. It is the physical integration of electrical and hydraulic systems as well as flight controls, with each laid out in relation to the actual configuration of the aircraft, and all components installed at the same place as they would be on the real airframe. The actual cockpit for the *Iron Bird* is typically displayed by simulators along with a mobile visual system. From this flight deck, the *Iron Bird* can be "*flown*" like a standard aircraft, with a computer generating the aerodynamic model and environmental conditions such as air density, air temperature, airspeed and Mach number.

The *Iron Bird* allows engineers to confirm the characteristics of all system components as well as to discover any incompatibilities that may require modifications during early development stages. Additionally, the effects and subsequent treatment of failures introduced in the systems can be studied in full detail and recorded for analysis [5].

Due to the increasing power of simulation technologies, and thus more and more accurate models of the physical components today, the "*hardware*" parts in the *Iron Bird* are replaced by virtual models. This allows system designers to use the concept of an *Iron Bird* in earlier development cycles, even when some physical components are not yet available. Extending this idea further along all phases of the life cycle leads to a complete digital model of the physical system, the *Digital Twin*.

The term *Digital Twin* was brought to the general public for the first time in NASA's integrated technology roadmap under Technology Area 11: Modelling, Simulation, Information Technology and Processing [6]. In this report the future development direction of modelling and simulation was outlined:

> A Digital Twin is an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including propulsion/energy storage, avionics, life support, vehicle structure, thermal management/TPS, etc. Manufacturing anomalies that may affect the vehicle may also be explicitly considered.
>
> In addition to the backbone of high-fidelity physical models, the Digital Twin integrates sensor data from the vehicle's on-board Integrated Vehicle Health Management (IVHM) system, maintenance history and all available historical/fleet data obtained using data mining and text mining. By combining all of this information, the Digital Twin continuously forecasts the health of the vehicle/system, the remaining useful life and the probability of mission success. The systems on-board the Digital Twin are also capable of mitigating damage or degradation by recommending changes in mission profile to increase both the life span and the probability of mission success [6].

Along with NASA's ideas, the US Air Force published similar ideas [7] establishing the *Digital Twin* is part of the USAF long-term vision addressing a time frame of the next 30 years. The general idea is that along with every plane a digital model is delivered, specific to the individual plane. Being "*specific to the tail number*", this digital model includes all deviations from the nominal design. The digital model will also be flown virtually through the same flight profiles as recorded for the actual aircraft and the data will be provided by the structural health monitoring (SHM) system of the flying plane. Comparing actual sensor readings with modelling results at critical locations allows engineers to update, calibrate and validate the model. Changes in the plane configuration like unanticipated damage will be added to the digital model. The *Digital Twin* hence always represents the current state of the actual aircraft. The main application of this digital model is to determine when and where structural damage is likely to occur and thus to predict the optimal maintenance intervals.

The aspect of a seamless coverage of the life cycle with digital models is not mentioned in the above publications. The USAF also introduced the concept of a *Digital Thread* [8] for the acquisition of new material to focus on rapid fielding, the development, employment and integration of digital design tools across the acquisition life cycle. The *Digital Thread* is the creation and use of a digital surrogate of a material system that allows dynamic, real-time assessment of the system's current and future capabilities to inform decisions in the Capability Planning and Analysis, Preliminary Design, Detailed Design, Manufacturing and Sustainment acquisition phases.

The digital surrogate is thus a physics-based technical description of the system resulting from the generation, management and application of data, models and information from authoritative sources across the system's life cycle. A *Digital Thread* capability is enabled through technical advances in modelling, data storage and analytics, computation and networks. The *Digital Thread* concept creates informed decision making at key leverage points in the development process that have the largest impact on acquisition programs. This would lead to earlier identification and a broader range of feasible solutions; a structured assessment of cost, schedule, and performance risk and accelerated analysis, development, test, and operation.

Looking at the basic message of these descriptions, the definition of the *Digital Twin* and the *Digital Thread* are nearly the same, only differing in position during the life cycle. Both concepts make use of all available virtual models which are interconnected to provide the best possible information. Also, additional data either from live systems or from historic data are used. Whereas, the *Digital Thread* concept is used to support the acquisition phase, and implicitly the design of new aircraft, the *Digital Twin* should support its operation and service. However, as both concepts are based on the same idea using simulation models to predict the behaviour of the real system, in the following only the term *Digital Twin* will be used regardless of the life cycle phase where the concept is used.

5.4 The Digital Twin from the Simulation Viewpoint

The general vision of the *Digital Twin* refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information, which could be useful in later lifecycle phases. This is from a technical point of view not feasible. The data volume is too huge, diverse and totally unstructured. Furthermore, new applications in later phases require specific preparation of data and information in previous phases. A specific architecture of a *Digital Twin* is necessary.

Before we discuss this aspect, we will describe the *Digital Twin* vision from a simulation viewpoint. The *Digital Twin* refers to a description of a component, product or system by a set of well aligned executable models with the following characteristics:

- The *Digital Twin* is the linked collection of the relevant digital artefacts including engineering data, operation data and behaviour descriptions via several simulation models. The simulation models making-up the *Digital Twin* are specific for their intended use and apply the suitable fidelity for the problem to be solved.
- The *Digital Twin* evolves along with the real system along the whole life cycle and integrates the currently available knowledge about it.
- The *Digital Twin* is not only used to describe the behaviour but also to derive solutions relevant for the real system, i.e. it provides functionalities for assist systems to optimize operation and service. Thus, the *Digital Twin* extends the concept of model-based systems engineering[6] (MBSE) from engineering and manufacturing to the operation and service phases.

We will discuss four aspects of the *Digital Twin.*

- Principle approach and benefit
- Architecture of the *Digital Twin*
- Lifecycle aspects
- Digital Twin and value chains.

5.4.1 Principle Approach and Benefit

In Fig. 5.3 the principle approach of the *Digital Twin* is shown. Existing IT systems like PLM, PDM and SCADA[7] systems store and provide huge amounts of information

[6]"*Model-based systems engineering (MBSE) is the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases*" [9]. So a core idea of MBSE is to use digital models to capture interactions of single subsystems and components at a system level. The system behaviour is tested against these models throughout the product development process.

[7]Product lifecycle management (PLM), Product data management (PDM), Supervisory Control and Data Acquisition (SCADA).

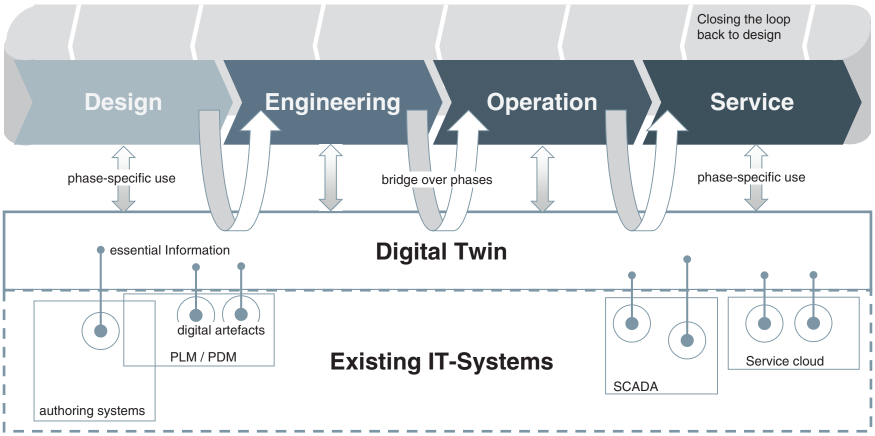

Fig. 5.3 The Digital Twin uses the essential information originating from different IT systems and makes it available for succeeding phases

coming from multiple authoring tools and sources, e.g. user requirements, CAD applications, operation data. The *Digital Twin* uses this digital information and makes it available as data and simulation models. Therefore, the *Digital Twin* includes the relevant data for processing phase-specific simulation tasks. In addition it contains just the essential information which is required for succeeding steps and phases. In this way the *Digital Twin* is smart, increases productivity and leads to new offerings during operation like assist systems and service applications. Furthermore, the Digital Twin can close the loop from operation and service back to design of new products or updated revisions.

Nevertheless, the *Digital Twin* is a highly dynamic concept growing in complexity along the life cycle based on the application of MBSE concepts. The *Digital Twin* is handed over with the product or even before. During operation it is the basis for simulation-driven assist systems as well as control and service decisions in combinations with smart data approaches. The concept of the *Digital Twin* is independent of manifestations or specific realizations.

5.4.2 Architecture of the Digital Twin

The goal of the *Digital Twin* is to prepare solutions for different but specific objectives and questions. These questions can arise in all lifecycle phases. For instance in the design phase, if the functionality of different components should be validated in a simulated interplay. However, the main benefit of the *Digital Twin* is expected in later phases. Therefore, the *Digital Twin* is a product feature, which is planned from the early stages. Also its primary use is defined and so limited to solve specific questions.

This requires that a *Digital Twin* architect describes the purpose(s) of the *Digital Twin*. Derived from this goal the tasks are defined, which are later executed to answer the questions. The final step is the specification of needed data and simulation models, which builds the architecture of the *Digital Twin* for a concrete application and set of purposes. A positive side effect of such a well defined *Digital Twin* structure is that in some cases new applications—which may not have been initially thought of—can be realized as well, based on the available (and persistent) information provided by the *Digital Twin* architecture.

However, the *Digital Twin* is still an abstract concept that allows a better component, product or system development. The underlying methodology is based on several aspects. The first is model based development. The information exchange is no longer focused on documents; instead models are used as a compact means to exchange information and interdependencies. Another important aspect of the methodology is the fact that models can be used in different situations as they are modular and have standardized interfaces (e.g. FMI [10]). A model management system keeps the single models up to date as changes occur. Also, the model management system supports the coexistence of different models with different fidelity and allows choosing the right model for the right application. Choosing the right model for a "*good enough simulation*" means that the model with that granularity is chosen, that is just fine enough to answer the design question, but not finer. Further, algorithms for the analysis of real-time and historical data are included as well.

5.4.3 Lifecycle Aspects

The relevant parts of the *Digital Twin* have to be designed in parallel with the development and physical realization of the observed system. As described above a *Digital Twin* simulation architect defines in the very beginning the structure and interfaces of all simulation models to be contained in the *Digital Twin*. This structure combines the single digital artefacts into a comprehensive functional and physical description. This structure is guided by the intended application fields for the *Digital Twin*. Only the relevant models are included and prepared, other digital artefacts are still contained in the existing IT systems like PLM. As the development continues the structure is filled with the real models and associated data. In the end the *Digital Twin* becomes part of the physical product. This procedure is enabled by a consequent use of MBSE techniques.

In this way the *Digital Twin* is part of the *Digital World*, see Fig. 5.4, and contains all information and models which are needed to solve tasks in later phases and to create new values, e.g. assistance systems for operators, user and maintenance personnel. The volume of the *Digital Twin* will increase during design and engineering phases. Depending on the specific component, product or system the transition to the operation or use phase can be realized in different ways. So it is possible, that not all data and models will be transferred. However, the collected and stored data in the *Digital Twin* will increase again during operation and

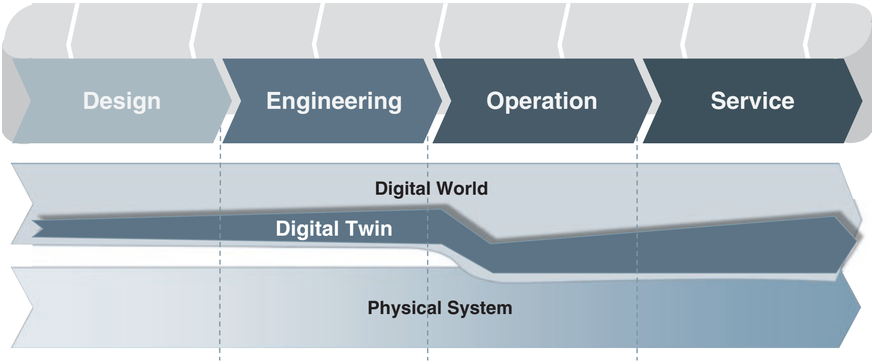

Fig. 5.4 *Digital Twin* evolves along phases and will be used as an integrated added value during operation and service

service phases. A special feature of the *Digital Twin* is that some of its content will become part of the real system, for instance an executable simulation model as an assist system module of the automation software. Thus, the *Digital Twin* implements the link-up of parts of the digital world with the physical system.

5.4.4 Digital Twin and Value Chains

We have already stated, that *Digital Twins* will be elaborated for—at least—components, products and systems. If we take a look to value chains, this means that *Digital Twins* will overlap in particular at specific points of different value chains. A good example is a production system. The equipment of a production system consists of different production units, which are products from other companies. *Digital Twins* of these products can be useful for the (virtual) commissioning of the productions system and also for the operation of the production system, e.g. for maintenance planning.

From a technical perspective *Digital Twins* have to skip borders of legal entities and in many cases to bridge between different proprietary data formats. Similar challenges and opportunities are visible on the production site. The producer needs parts and semifinished products and delivers his goods to customers, which use the product as end customer or for his production.

This leads to the consequence that the *Digital Twin* has to be modular. This modularity is used to transfer data and information into other *Digital Twins*. Especially in late phases (production, operation) where the *Digital Twin* has already gained lots of data lies the main application for the *Digital Twins*. For example, product design data can be used for service lifetime calculations and the product structure can be used to optimize the assembling in production either for the single components but also for large systems.

The same data and information structures can, in such an environment, exist in several models in parallel, as the modular structure of the partial models, is not always employed to the full extent. This has to be decided on a case by case situation. Each *Digital Twin* relates the essential part of the existing data and information (from existing IT systems) and makes them usable for its specific purpose.

5.5 Use of Digital Twin: Several Aspects During Life Cycle

In this section we show how the change from simple mechanical or mechatronic components towards mechatronic systems will occur, and how the comprehensive *Digital Twin* influences this transition. As an illustrating example, one can think of an electromotor as a mechatronic component and the combination of the motor, driving electronics and software as a mechatronic system.

In contrast to current development philosophies dominated by the engineering of details, in the future the system view and the interconnection between the different development phases will become more important. Simulation will become an important method for the whole life cycle.

5.5.1 Design Phase

During the concept design of the motor, a number of data and models are created which lay the foundation of the *Digital Twin*. The design is mainly determined by high-level requirements and experience with former developments. This information is used for a first abstract design mainly from a functional view of the motor. Here it is not yet decided, how the concept will be realized (e.g. in software or in hardware). In further detailing steps, based on the requirements or assumptions, the design is concretized. During all subsequent phases the current design has to be validated against the assumptions and requirements. One possible mean for validation is virtual prototypes, which mirror the current development state. As the development goes on, the virtual mirror image grows as well.

In the example of the electro-mechanic drive system, the basic requirements and the functional decomposition of the design can be modelled in a structured way using system description languages like SysML [11]. The dependencies and mutual interactions of the functions and requirements are shown, which helps designers to react quickly with a minimum of errors when requirements change. Many, if not all consequences of the changes can be identified before unnecessary detailing is done, especially if automated checking is implemented—which by the formal nature of the system description is possible even for large complex systems. In the further detailing of the design—when first decisions are made, by which the functions are realized, the virtual representation of the design also has to be detailed.

5.5.2 *Engineering Phase*

In the next development phase, additional engineering data including executable simulation models are created. As the engineering questions are now more specific, the simulation models also have to include further details. There may exist several different models for the same physical component, depending on the dedicated question they are created to solve. For successful engineering of complex systems, domain specific models have to be used together with extended system models, which include the functionality realized in software as well.

In the case of the motor system, many simulation models are created. There are mechanical models to examine the mechanical stability of the rotor or the motor mounting. Electrical models are used to calculate magnetic fields and the resulting forces. Thermal models calculate heat generation due to electrical losses. Other models describe the electrics and automation, and system models simulate the whole drivetrain including gears and bearings.

As the complexity of the objects to be designed increases and more and more disciplines and people are involved, the need for consistency among these models increases. In an ideal world all information should be stored in a unique place—not necessarily at the same physical location—to provide a consistent source and all models should also use this source for all input. This information includes not only the initial design parameters but also all models which are created during the development. However, this is often not possible for real systems. But at least a common awareness among all stakeholders of the development process about commonly used information is indispensable for a successful development of next generation mechatronic systems. The *Digital Twin* as a common repository for all digital artefacts supports this.

The latest phase of product engineering is the integration of the different components to the full system. Here it is necessary that all components fit seamlessly together. Usually the components are not ready at the same time or are not available for testing as it is, for example, with the environment where the product (electromotor) is finally installed. In this case, models from the Digital Twin can be used to replace physical components in the system integration test for example, as it is done with the *Iron Bird*.

Mounting difficulties when parts from external suppliers have to be integrated can easily detected in advance if a digital representation of the component is provided along (or in advance) with the physical part. Such a procedure is supported by dedicated light-weight formats (e.g. JT [12]), that reduce the exchanged information to the necessary amount. So the model from the supplier can be integrated into the model representation from the *Digital Twin* easily and checked for any inconsistencies. This procedure works not only for physical components. Software for automation can also be tested in advance using the virtual representation of the real system (i.e. virtual commissioning).

Even the final operating environment can be simulated by numerical models to have a realistic final test before the deployment of the final product.

5.5.3 Model Reuse for Operation

The main purpose of the *Digital Twin* for mechatronic systems is that the information created during design and engineering is also available and ready for evaluation during the operation of the system. This is nowadays often neglected, as design and operation are mainly disconnected life cycle phases from the point of data usage. An obvious example for model reuse is continuous product improvement, for example, if the intended use of the product changed and product modifications are necessary. In this case the existing models can be used and slightly modified.

On the other side, if data from operation are also collected systematically as part of the *Digital Twin*, they can be used to verify and update the existing models for real operation conditions such that the gained knowledge can be used for next generation of products as well. As the *Digital Twin* is already planned from the earliest time, the suitable interfaces to interact with real data are already in place. Thus, the real data can be used as verification input for the simulation models and lead to their continuous improvement.

Online condition monitoring is also a growing application field for the *Digital Twin*. For more and more mechatronic systems, sensors are installed to monitor the operation and give early warning of a malfunction [13]. However, only relying on sensor data is sometimes not sufficient. Especially, as particular values may not be accessible for a direct measurement. In this situation the simulation models from engineering, provided by the *Digital Twin*, can be reused after some modifications. The existing models have to be streamlined, to cope with the real-time data and new requirements from operation. Based on the real sensor data the simulation models extend the measurements towards a "*soft sensor*", which can also acquire virtual sensor data, where real measurements are technically not possible.

By using the simulation models, it is also possible to interpret the measurements in a different way, rather than just detecting deviations from the norm. Several modes of failure can be simulated for the current situation trying to reproduce the actual measurement signals. The comparison of the simulated signals with measured ones can help to identify the failure mode.

5.5.4 Service Phase

As the *Digital Twin* provides a smart view on the available system information, models and results from earlier life cycle phases are accessible also for users of different disciplines.

During engineering the product has to be designed such that it can withstand a given load. The proof is done via simulations. However, additional information from the simulation can be deduced with little extra effort, like the expected lifetime of the part or how "*well*" the design criteria are fulfilled. Parts which fulfil these conditions only tightly are natural candidates as causes for malfunction. The availability of this information allows an improved and enhanced service process, as the most important (with highest likelihood needed) spare parts are already known in advance.

Together with data from online measuring, the simulation models and operation history provided by the *Digital Twin* are also the base for more flexible service planning. Depending on the actual load exposure, the lifetime budget of the relevant parts—accounted for in the *Digital Twin*—is deduced. Therefore, a comprehensive picture exists of the condition of the system which also eases the inspection planning and spare parts logistics even before a failure occurs.

5.6 Conclusion and Outlook

For mechatronic systems new and novel goals will emerge, e.g. as caused by cyber-physical systems. These are networked systems, which interact together, and realize new functionalities by cooperation. Aspects like autonomy will be important and software-driven configuration and use (digitalization aspects) will increase. Therefore, mechatronics will evolve further. Mechatronic products will gain a more complex structure and will have more computing power and network connectivity. This leads to the extended design challenges where simulation will be a key technology to master it. Simulation will not only become an essential part during the development of mechatronic systems but it will also become a part of the systems themselves as well. It will be applicable and executable during the operation of the mechatronic systems for operation support and new service applications.

The classical goals will still remain valid: time reduction (development time, time-to-market), adherence to quality and fulfilment of customer needs and requirements.

Realizing the simulation aspects of the *Digital Twin* is a key vision from our point of view to make significant steps forward to reach these goals. It is the smart way to gather and provide all information stored in existing IT systems which is essential for life cycle over spanning use. The benefit of the *Digital Twin* concept will be the improved consistency, a seamless development process and the possibility of reuse in later life cycle phases. Further, there is the increased potential for using the complete set of information in the development of next generation products.

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Chapter 6
Design Processes of Mechatronic Systems

Matthieu Bricogne, Julien Le Duigou and Benoît Eynard

6.1 Introduction

Nowadays, in order to design innovative and multidisciplinary products such as mechatronics systems, the product development process needs to be rethought or at least adapted. Current processes are based on organizational models, business standards IT solutions and so on and have to take into consideration that electronics and software represent an ever increasing part of the final product [1], as illustrated in Fig. 6.1. In this context, traditional mechanical engineering, electrical/electronic and software methods cannot just be coordinated, and common interdisciplinary design approaches have to be proposed. These approaches will be influenced by several trends such as agile design methods [2], servitization[1] of products [3] and increasing demand for mass-personalized products [4].

This chapter is divided into two main sections. The first reviews some of the current design processes of mechatronic systems in order to point out the heterogeneity of practises and the gap remaining to integrate these discipline specific practises. The second section then presents several industrial trends which will, from our point of view, greatly influence the future of mechatronic systems design.

[1]Servitization (also found as servicization or servification), refers to a paradigm of transition of a product centric offer to a combined product-service offer, underpinning a change of the business model for the company.

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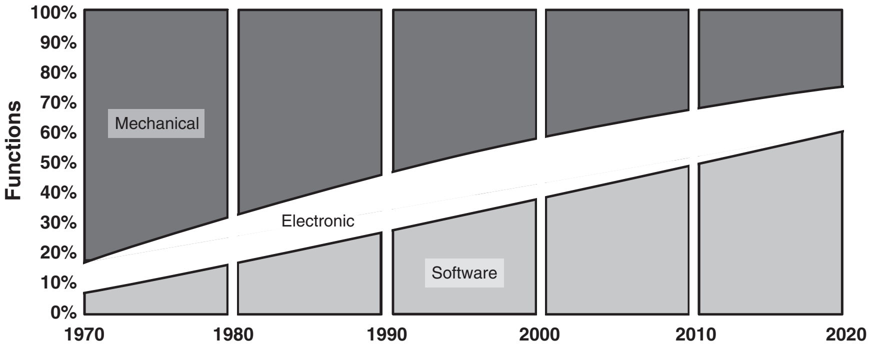


Fig. 6.1 Function assignment over time in the development process of mechatronic systems (adapted from [1])

6.2 Current Design Processes of Mechatronic Systems

Mechatronic systems have evolved from electromechanical systems with discrete electrical and mechanical parts to integrated electronic–mechanical systems with sensors, actuators, and digital microelectronics driven by sophisticated software modules [5]. This evolution is driven by changes in market conditions, expressed as new demands such as integrating more functions into the product, reducing the weight and size of the product, increasing reliability and so on.

Despite these deep evolutions, the main development process, called here the new development product (NPD) process, is not much changed over time. Although new requirements for transversal communication between all participants from different disciplines, engineering activity and cultures are becoming increasingly important, the NPD main steps have largely remained the same. The next section will present some of these NPD process models.

6.2.1 New Models of Product Development Process and Mechatronic Systems Specificities: Focus on Multidisciplinary Integration

Models of product development process have generally emerged from the mechanical communities [6–8]. Despite this historic connection, the titles of these models and the step names illustrate the fact that the originators want to present these process models as generic, whatever the type of product developed, or the type of technology used. They generally speak of "*engineering design*" and not of "*mechanical design*". Here, only one product development process model that is presented in Fig. 6.2 [7] has been chosen as it is an questionable standard, but a more general summary is also presented by Howard et al. [9]. Based on this model, specificities of mechatronics systems design are described in this section.

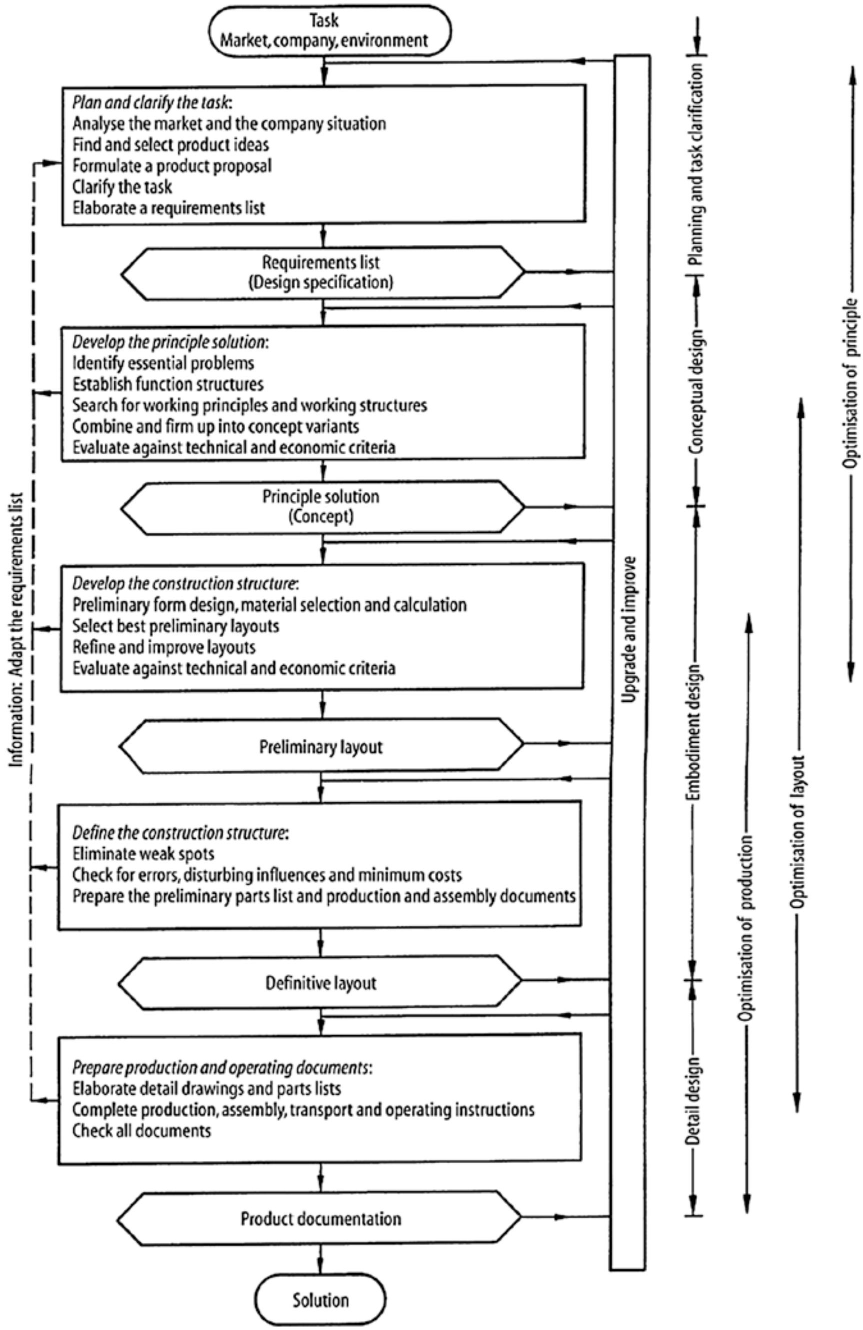


Fig. 6.2 Steps in the planning and design process [7]

Needs Clarification and Conceptual Design Phases [9]

Design of a mechatronic system requires multidisciplinary collaboration. To deal with such multidisciplinary design issues, systems engineering has been proposed as an interdisciplinary approach [10]. In the mechatronic context, systems engineering is mostly used to consolidate a requirements list, to establish function structures and to propose preliminary product architecture. For instance, SysML [11] and associated methodologies [12] are often presented as a solution to support the need establishment phase whereas model-based systems engineering (MBSE) activities [13] and Design Structure Matrix [14] are used to support system architecture elaboration.

Embodiment Design and Detailed Design Phases [9]

During the embodiment design and detailed design phases, one of the biggest remaining challenges is the data management. For these phases, most of scientific efforts in the mechatronics field concern product model dedicated to mechatronics (Core Product Model, MOKA, etc.) [15] to store information, unique bill of material (BOM) to federate expert contributions (Fig. 6.3), standards creation/usage to support data exchange [15, 16], consistency management between expert's models [17] and so forth.

This focus on the product data management is mainly due to the fact that methodologies remain specific for each discipline. Some of these discipline specific methods are presented in the next section.

6.2.2 Models for Mechatronic Development Process

As seen in the previous sections, a strong feature of the design process of mechatronic system is that it requires a multidisciplinary and holistic development process. Despite this fact, few specialized models of mechatronic development process are available in the literature. For several decades, different models, such as the *Waterfall* or cascade model [18], the spiral model [19, 20] or the V-model [21] have been proposed to support the design systems. This type of model can indeed support the design process at a very macroscopic level, but it does not support collaboration between designers from different disciplines. In particular, the multidisciplinary integration, such as hardware–software integration, is not supported.

Some specialized design process models for mechatronics have been exposed and compared [15]. The most well known of these processes, the V-Model [22], presents a general flow for the product development process. To understand how this process is implemented by industrials, Aca et al. [23] detailed the way the tasks are dispatched between the different disciplines according to project management principles, Fig. 6.4 illustrates this situation. Teams are then able to work concurrently on each sub projects and the multidisciplinary integration is treated at the late stage of the process.

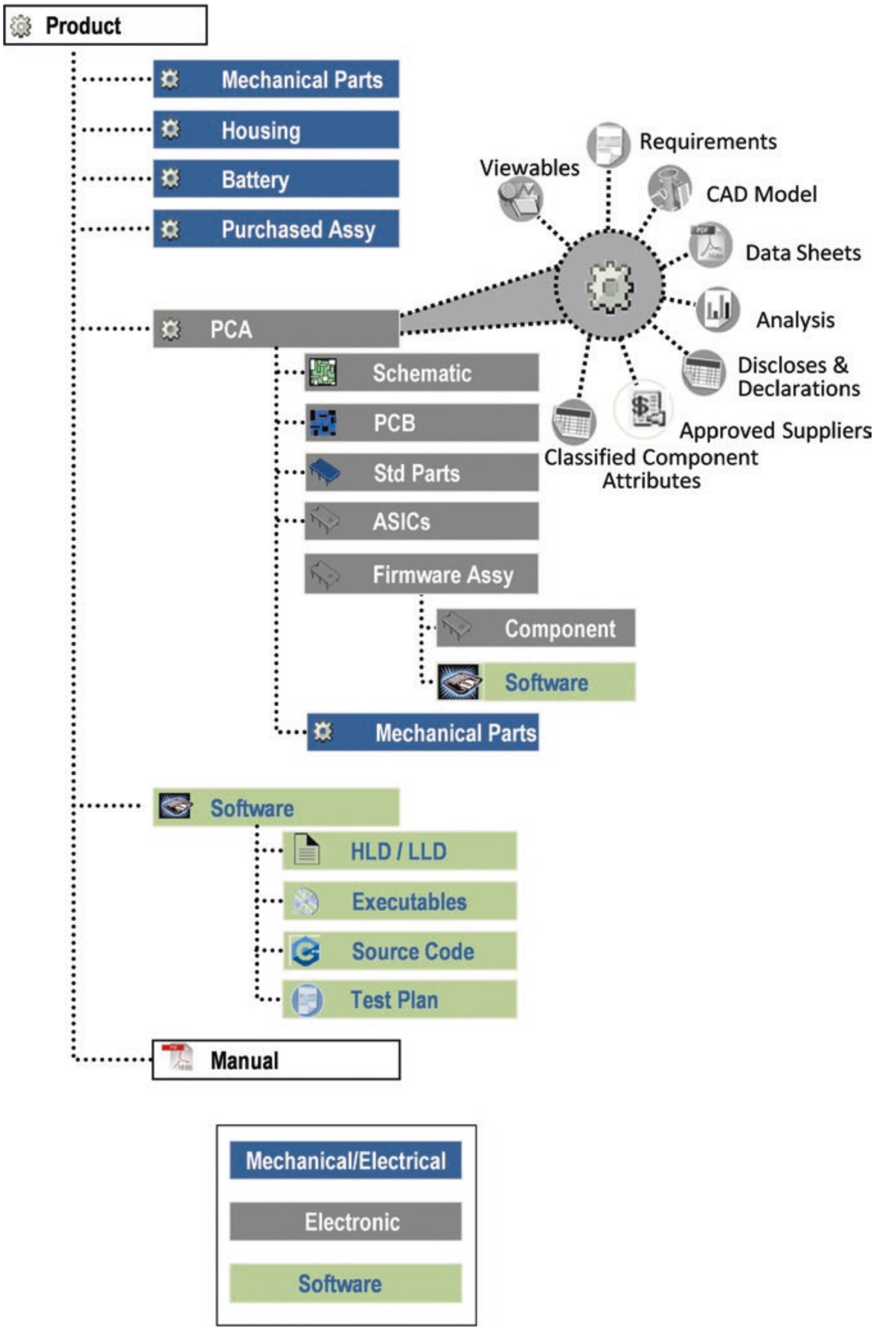


Fig. 6.3 Unique bill of material for the whole mechatronics system (adapted from PTC: mastering change and configuration management for business advantage (2013). www.ptc.com. Accessed 20 November 2015)

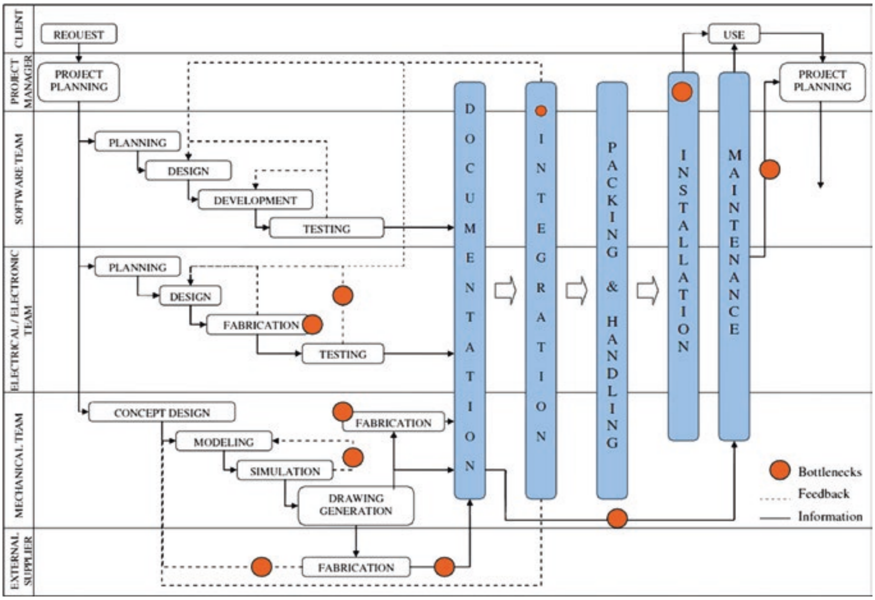


Fig. 6.4 Mechatronic system development process based on discipline division [23]

In these first sections, development processes main characteristics for E/E and software engineering have been presented and positioned relatively to NPD general process. The heterogeneity of these processes has been underlined to demonstrate and illustrate the remaining challenges for mechatronic system design and integration. In the next section, some of the current scientific approaches attempting to improve multidisciplinary integration are presented in order to illustrate the remaining work in this field.

6.2.3 Further Challenges for Integration of Mechatronic Systems: Current Research Approaches

In the previous section, classical mechatronic design processes were exposed and appear to be very sequential and discipline specific. But developing mechatronic systems requires intensive collaboration between engineers from different domains [24, 25] . Therefore, there is a need for concurrent engineering approaches with an integrated strategy.

The main challenges in design of mechatronic systems [26] can be summarized as

- Exchange of design models and data;
- Cooperative work and communication among the design engineers;
- Multidisciplinary modelling;

- Simultaneous consideration of design from different disciplines;
- Early testing and verification;
- Persistence of a sequential design process;
- Need for tools and methods supporting multidisciplinary design;
- Support of the design of control software.

Some design methods seems to be more adequate for the design of mechatronic systems (Systems Engineering, Agile Methods, MBSE, etc) and are adapted in recent works specifically for this purpose.

Systems engineering has been proposed as a multidisciplinary approach to enable the realization of complex systems [27] apply extensions for every design phase based on the VDI guideline 2206 in order to improve the development of systems controlled by a programmable logical controller. The Requirement–Functional–Logical–Physical (RFLP) approach is a specific V-Model derived method, particularly adapted to mechatronic systems design and formed of four phases (requirement, functional, logical, physical) which are each supported by different technical tools aiding the designers [27]. Zheng et al. [28] propose a two level process based on V-Model and hierarchical modelling, focusing on interfaces to improve multidisciplinary integration in detail design. System engineering improves cooperative work and communication among the design engineers at the early stages of the design process, multidisciplinary modelling, early testing and verification and provides a set of tools and methods supporting multidisciplinary design. Nevertheless, the detailed design is still very domain specific and needs further developments.

Agile methods came from software development and are mainly driven by "*accelerate delivery*" realized by focusing on small steps. Contrary to established methods as V-Model based on stage-gate with strict processes and heavy documentation, agile methods principles are based on interactions between individuals, customer collaboration and working products (or prototypes) [29]. But agile methods in mechatronics systems development is less explored than in software development. However, few examples exist, as [30, 31] that present agile methods applied on industrial cases. Stelzmann [32] discus appropriate context to the application of agile methods in system engineering context. In this context, Bricogne et al. [33] propose a framework including engineering actions management, trans-disciplines activities management, data exchange and collaboration to support agile methods applied to mechatronic systems design.

Agile Methods improve cooperative work and communication among the design engineers, multidisciplinary modelling, simultaneous consideration of design from different disciplines, and early testing and verification. Nevertheless, large-scale systems, traceability and safety and distributed environment imply the impossibility to use agile methods, but the agile principles (welcome changes, self-organizing teams, etc) may still be applicable.

MBSE has attracted numerous researchers' attention recently. It is considered as a significant methodology for the design of mechatronic systems with increasing complexity [34]. The Object Management Group's Unified Modelling

Language and System Modelling Language (SysML) has been recently widely used to support the MBSE [35]. Some extensions have been developed for SysML to support the specific requirements of design of mechatronic systems, such as automatic simulation [36], design making process [37] etc. MBSE improves exchange of design models and data, multidisciplinary modelling, simultaneous consideration of design from different disciplines, tools and methods supporting multidisciplinary design and support of the design of control software. However, current studies on MBSE mainly focus on early design phases and seldom involve the detailed design phases. Moreover, MBSE are more adapted to complex systems but it is still missing effective and user friendly tools for such development.

Mechatronic systems design new processes are widely explored by academics and industrials but none of them overpass all challenges, especially in the detailed design phases.

6.3 Future Trends for the Design of Mechatronic Systems

In the previous sections, some current scientific approaches attempting to address organizational challenges for mechatronic system design have been presented. In the future, new challenges will have to be taken into consideration. These challenges will relate to several trends, such as the ever increasing software element in products (Fig. 6.1) and the necessary collaboration between systems.

6.3.1 Hardware/Software Design Methods Convergence: Cyber-Physical Systems Versus Mechatronic Systems

The science of Cybernetics has given birth to a type of system referred to as a cyber-physical system (CPS). These CPSs refer, according to Rajkumar et al. [38], to a next generation of systems that require close integration of information, communication and control technologies to achieve stability, performance, reliability, robustness and efficiency in the management of physical systems of many application areas [38]. Although CPSs development brings up specific issues and challenges, a large majority of integration problems encountered are similar to those identified in the design of systems involving multidisciplinary teams as required for mechatronic systems. Despite this observation, the mechatronics and CPS communities at present seem to only slightly interact and share their expertise. The explanation proposed here is that mechatronic products are historically electromechanical products introducing more and more electronics and software while CPSs are historically the "*Cyber-Systems*" [39], which are more and more interacting with physical reality, Fig. 6.5 shows the predominance of the software aspect of this vision.

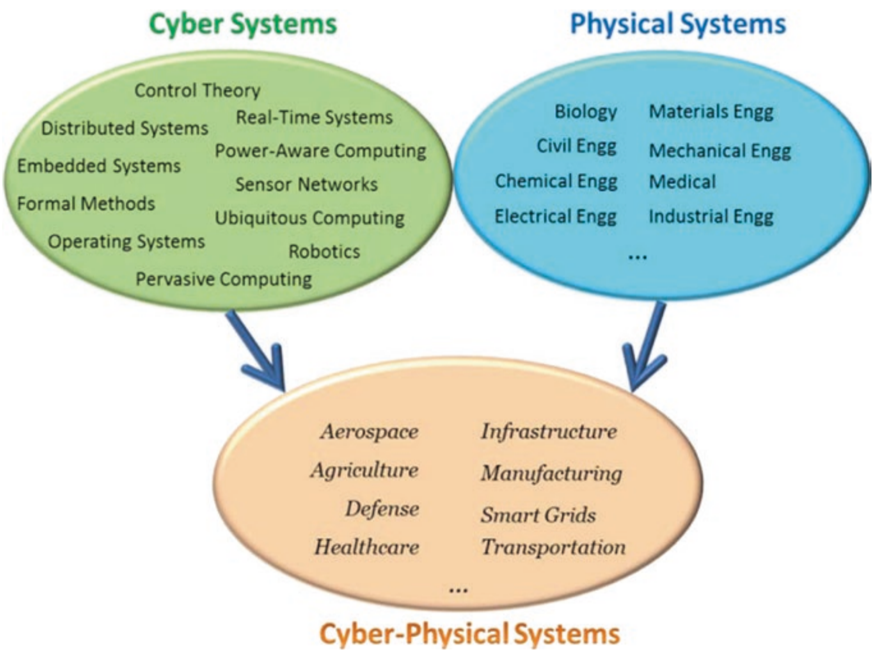


Fig. 6.5 Cyber systems actors' vision on cyber-physical systems [39]

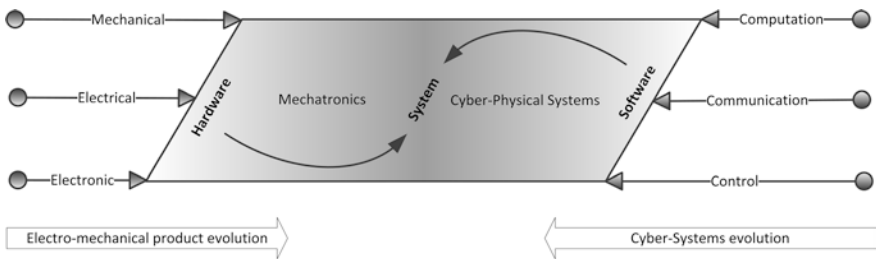


Fig. 6.6 Co-influence of mechatronic system and CPS

As can be seen, mechatronics and CPSs challenges and research issues are complementary. While mechatronics is particularly focused on the hardware part of a system, CPSs remains focused on the software parts. Nevertheless, these two areas share a common goal which is to design and produce integrated systems. Figure 6.6 summarizes this convergence between CPS and mechatronic systems.

6.3.2 The Role of Mechatronics in the Internet of Things Trend

This convergence between mechatronic systems and CPSs is also subject to the pressure of the Internet of Things (IoT) trend, "*The connection of physical things to the Internet makes it possible to access remote sensor data and to control the physical world from a distance*" [40]. Thanks to this definition, we can understand the future role of mechatronic systems into this (r)evolution. IoT is based on smart objects, which can be considered as a mechatronic system connected to the Internet.

The need for new devices or for the integration of sensors or/and actuators in new generation of existing products will probably greatly increase the development of the mechatronics field. Whereas mechatronics' application was sometimes considered for specific and complex systems, this pervasive deployment of smart objects [40] will greatly amplify the need for mechatronic systems. However, some authors argue that "*there will need to be significant changes to the way mechatronic, and related, systems are designed and configured*" [41] to be fully integrated in the IoT trend.

They underline that "*increasing complexity while managing the transfer of functionality, particularly from the mechanical domain to the information technology and electronics domains, has long been an issue facing system designers*" [41, 42]. This state will force "*practitioners and educators to further review the ways in which mechatronic systems and components are perceived, designed and manufactured. In particular, the role of mechatronic smart objects as part of an IoT based system in which the structure is defined by context is resulting in an increased and increasing emphasis on issues such as machine ethics, user interaction, complexity and context as well as with issues of data and individual security*" [41].

From a technical point of view, if every mechatronic system can be individually identified and can conform to a standard protocol, the interoperability of the systems will increase and make systems even more autonomous and intelligent. New applications can then be envisioned. Another perspective relies on new synergistic services offered by mechatronic products compared to an isolated embedded system. Both these new opportunities are detailed in the next sections.

6.3.3 The Role of Mechatronic Systems in the System of Systems Trend

The role of mechatronic systems in the system of systems (SoS) can be defined as "*large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal*" [43]. Systems participating in a SoS are independently designed and can operate autonomously [44]. Following this definition, mechatronic systems and CPS can be considered as components of SoS (see Chap. 10).

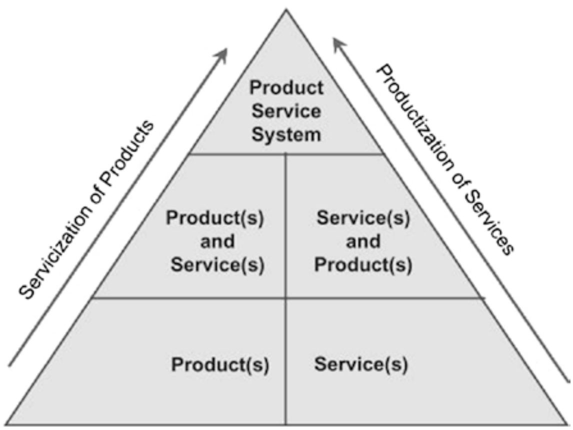
Main characteristics of SoS are defined in [44]. A SoS performs functions which are not achievable by single systems (so called emergent behaviour). SoS are geographically distributed, such that all participating systems need to exchange data in a distributed and remote way. This implies the emphasis of previous sections on CPS and IoT trends and the next generation of connected mechatronic systems. Another characteristic is the evolutionary development. This means that the SoS offered services and purposes change over time and mechatronic systems must be able to enter or leave the SoS during run-time. Managerial independence is another characteristic of a SoS. The mechatronic systems are design independently and manage their own goals.

This implies new methods and tools to develop SoS that could constrain mechatronic systems design. SoS engineering deals with planning, analyzing, organizing and integrating the capabilities of a mix of existing and new systems into an SoS capability greater than the sum of the capabilities of the constituting parts [45]. New mechatronics systems should enable this SoSE, with standardized interfaces and cooperation enhancement.

6.3.4 The Role of Mechatronics in the Servitization Trend

In order to improve customer loyalty and to optimize the balance between the offer and the customer's requirements, significant numbers of industries are shifting from a product centric approach to a bundle of products associated with and to services. This is presented as a way to achieve objectives such as risk reduction, competitiveness exposure reduction and sustainability through business model evolution. The shift towards an integrated offer of products and services is illustrated by both concepts of *productization* and *servicization*, in a paradigm of a transition from a service or a product to an "*integrated bundle of products and services*" called a product-service system (PSS) [46]. These evolutions are presented in Fig. 6.7.

Fig. 6.7 Evolution of the PSS model [3]



In this context, mechatronics systems have a great role to transform product into a platform supporting services. Even if the system is neither connected all the time (IoT) nor able to interact autonomously with other systems (SoS), the fact mechatronic systems is able to transform physical product into an intelligent system allows to envision new perspectives. Some authors recently presented some approaches to consider the service during the mechatronic system design [47].

6.3.5 The Role of Mechatronic Systems in the Factories of the Future

Regarding the challenges of the factories of the future (FoF), the mechatronic systems can be viewed as the backbone for smart integration of the new factory models which is also strongly supported by the vision of Industry 4.0 [48, 49].

Since the end of 2000, the intensive use of digital factory technology [50] allows the design of agile production lines and complex manufacturing systems fully integrating mechatronics systems based on smart sensors, actuators, drivers and controllers allowing the communication machine to machine, the remote control of manufacturing operations, the self-diagnosis faults before failure of systems and an efficient management of energy usage in the production plants. In factory and production process environments, virtualization of operations thanks to embedded mechatronic systems and large industrial internet connection via distributed networks and cloud computing enables the implementation and control of cloud manufacturing operations and services [51–53].

Increasingly, new machine tools, industrial robots, and production equipment are definitively based on mechatronic technology such as sensors, actuators drivers and controllers. Then, they become more and more autonomous to collect data and information for monitoring of operations and remote controlling of processes. Based on all these distributed manufacturing information and data, manufacturing execution systems (MES) will work in real time to enable an efficient, agile and flexible production management based on information and control alignment and interoperability with the enterprise resources planning (ERP) system [54, 55]. Benefits will be obtained in improving productivity, supply chain management, resource and material planning and product lifecycle management with the complete integration of information and communication technology (ICT) and industrial internet as support of enterprise information system [56, 57].

All these contributions based on the backbone of mechatronics integration in the factory and manufacturing plants will ensure the future generation of cyber-physical production systems and support the architecture of systems of manufacturing systems [58].

6.4 Conclusions

The chapter has dealt with new models for design processes of mechatronic systems and their future trends with novel applications. After a detailed presentation of the current models and standards of development processes for mechatronic systems engineering, the future trends for mechatronic system design are discussed. First, the new developments of mechatronics in the field of CPSs were considered. Second, the added-value of mechatronic systems for the implementation of the IoT has been detailed. Third, the role of mechatronics in the design and integration of SoS was presented as last research trend.

Last, regarding the applications, two very interested topics were considered with the integration of mechatronic systems in the servitization of products, on the one hand. On the other hand, the generalization of mechatronics as backbone of the FoF was discussed.

The future trends and models for the design processes of mechatronic systems have to be considered as unquestionable enablers for transformation of complex systems into CPSs or the global integration of the IoT. These design processes for mechatronic engineering have to support the development of the new services or the implementation of industrial internet for the FoF.

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Chapter 7
Design of Biomimetic Soft Underwater Robots

Aiguo Ming and Wenjing Zhao

7.1 Introduction

The evolution process for creatures is very, very long and contains many useful secrets and rationality mostly hidden in their structure, motion and configuration. Biomimetic mechatronic design is a useful approach for future mechatronic innovation, which can significantly enhance the performance of mechatronic systems. As an important issue for biomimetic mechatronic design, it is necessary to make a robot as soft as a natural creature to achieve more efficient, high-performance and creature-like motions. Compared to a conventional rigid robot, the design and control of a soft robot is difficult because the coupling between the flexible structure and surrounding environment should be considered, which is very difficult to resolve due to the large deformations and complicated and coupled dynamics. This is the main reason why design methods for soft robots have not been established, despite the many trial developments of soft robots that have been undertaken to date. The challenges for the design of biomimetic soft underwater robots based on numerical simulation considering the coupling between the flexible structure and surrounding fluid as well as control technologies are described in this chapter.

7.2 Basic Theory and Developments for Underwater Robots

Humans have had dreams for robots for many years, hoping that people can be replaced by robots for some work or tasks. In 1954, the first robot with point-to-point control was implemented by George Devol in the United States [1]. From then, the

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robot has come into human life and people's dreams begin to come true as robots start to play more and more important roles in many fields.

Due to the unknown underwater environment, many underwater robots have been designed and developed for seabed exploration, observation, leakage detection, military reconnaissance, rescue, environment protection, etc. [2–5]. Because of the complicated underwater environment and tasks, underwater robots need to have better mobility and motion performance in their special working environment. Underwater robots with simple moving mechanisms such as wheels and crawler tracks have not been able to meet the demands of the various complicated environments and tasks. These kinds of robots also have poor adaptability and flexibility, which can cause enormous energy deficiencies in their propulsion.

Today, many researchers are looking for biological inspiration to create a new generation of swimming automatons known as biomimetic underwater robots to achieve high efficiency, good mobility and manoeuvrability. A biomimetic underwater robot has to mimic the external shape, body structure, motion principles and behaviours of creatures in the underwater environment, and is able to undertake the work based on the creature's motion characteristics [5]. Engineers and scientists have thus concentrated on the design and development of biomimetic underwater robots mimicking swimming creatures [6–25].

As one of the most active fields in the development of science and technology, biomimetic underwater robots are achievements of interdisciplinary science including robot technology, microfabrication technology, biological science and hydrodynamics. Essentially, the biomimetic underwater robots are complicated systems ranging from metre to nanometre scale [10]. Many inorganic components (such as mechanical, electrical, hydraulic components) and organic bodies are utilized to build the robot system. The design of biomimetic underwater robots is particularly difficult for the operation and integration of these components to work efficiently, reliably and autonomously in the underwater environment.

The research on biomimetic underwater robots mainly encompasses two areas: the study of the basic theory and the development of biomimetic underwater robots with high speed, efficiency and mobility.

7.2.1 Propulsion Theories

In nature, there are thousands of species and forms of aquatic organisms. They have various morphologies and motion patterns and can be classified into three types: first, cilia propulsion used by many protozoa and coelenterates on the body surface; second, jet propulsion as with jellyfish and squid using the recoil force for propulsion by jetting fluid in the opposite direction; third, undulation propulsion where aquatic organisms swing their body to achieve the propulsive force. A large number of fish use this undulation approach for propulsion by swinging their body or caudal fins, pectoral fins and so on. This undulation propulsion is the main focus in much research into designing and developing biomimetic underwater robots.

Undulation propulsion is different from the propulsion mechanism of a conventional propeller. Reynolds number is a dimensionless number describing the relative importance between forces from fluid viscosity and fluid inertia, and is generally described by Eq. 7.1. According to the different values of Reynolds number, fluid flows are divided into different patterns. When $Re < 1$, the fluid viscous force dominates, and if Re is larger than 1000, the fluid inertial force dominates in fluid flow [26].

$$\mathrm{Re} = \frac{\rho U L}{\mu} \tag{7.1}$$

where U is the forward swimming speed of the fish; L is the length of the fish; ρ is fluid density and μ is fluid dynamic viscosity.

The swimming kinematics of underwater creatures involves different propulsion mechanisms, such as meandering propulsion with a travelling wave. These kinematics result from the complicated coupling dynamics between the forces from muscles and from the surrounding fluid. In the swimming motion of a real underwater creature, the muscles deform the soft body, which then applies a force to the surrounding fluid. In return, the fluid also applies a force on the soft body which changes the body shape. This interaction is repeated endlessly and propulsive force is generated as its result.

In order to model the deformation of a soft body from real creatures accurately, the forces mentioned above must be taken into account simultaneously. Few models have been proposed to solve this coupling problem due to its complexity [27]. Instead, according to the different swimming motions of real creatures, most theories define the creature body as a given shape to predict the fluid forces, such as theories used in fish-like robot design with the basic propulsion model classified either as a resistive model or a reactive model.

The resistive model is proposed by Taylor [28]. The thrust is estimated from the sum of the drag forces on the fish body with a travelling wave whose speed is larger than the forward swimming velocity. The body is divided into many segments along the body length. The drag force of each segment can be calculated by Eq. 7.2:

$$D = 0.5 C_{\mathrm{d}} \rho u^2 s \tag{7.2}$$

where C_{d} is the drag coefficient; ρ is fluid density; s is surface area of segment; u is swimming velocity including contributions from forward motion and lateral undulation.

The resistive model is built based on a quasistatic method using steady flow theory to predict the fluid force in the swimming motion. In this model, because the fluid inertial force is neglected, its applicability is restricted to a low Reynolds number. And because it is assumed that anterior segments of the creature do not affect fluid flow moving past the body, this model may not hold for the undulation of real fish. For the anguilliform type, because viscous forces play significant role, it belongs to this resistive model. The problems of the resistive models are discussed in detail by Webb [29]. Although this resistive model has some limitations for estimating resistive forces, it is important in the thrust generation of real creatures whose drag force plays the dominant part in the interaction with surrounding fluid [30] and may reduce the propulsive efficiency [29].

Later, the reactive model is presented to design a biomimetic underwater robot with a fish-like propulsion motion. The model deals with more realistic fish-type motions, assuming an inviscid fluid, that is, the fluid viscosity is assumed to be negligible. A two-dimensional waving plate theory was developed originally by Wu [31]. Based on the slender body theory stemming from aerodynamics, the elongated-body theory is formed and it is suitable for subcarangiform and carangiform propulsion modes of real fish.

The favourite mathematical model of fish swimming used in the design of a biomimetic underwater robot is the elongated-body theory developed by Lighthill [32, 33]. In this model, the force from the fluid induced by the lateral acceleration and deceleration of the undulating body is estimated based on acceleration reaction in which the surrounding fluid is regarded as added mass [34, 35]. Thus, this model is generally termed as the reactive model. Ignoring fluid viscosity, the average thrust power can be calculated using Eqs. 7.3–7.6 [32, 36]. The average thrust force can be approximated by thrust power divided by forward swimming speed.

$$P_{\mathrm{T}} = mwUW - 0.5mw^2U \tag{7.3}$$

$$m = \left(\frac{d}{2}\right)^2 \pi\rho \tag{7.4}$$

$$w = W - W\frac{U}{V} \tag{7.5}$$

$$W = \frac{\pi f A}{1.414} \tag{7.6}$$

where P_{T} is the thrust power; m is the added virtual mass per unit length; w is the velocity of water at the trailing edge; W is the rms value of the lateral velocity of the trailing edge; U is the forward swimming speed; V is the velocity of the body propulsive wave; ρ is the density of water; d is the span of the caudal fin at the trailing edge; f is the oscillating frequency of the caudal fin; A is the oscillating amplitude of the caudal fin.

The reactive model described above assumes that the undulating amplitude is small, so that the angles of the body with the swimming direction are close to zero. When the angles become large, more energy is lost into the wake around the fish body. A large-amplitude elongated-body theory developed by Lighthill considers this effect and motion with arbitrary amplitude [5, 33]. This theory is better suited to carangiform type of fish swimming, where the lateral motion amplitude of the caudal fin is large. The elongated-body theory assumes that the inertial force completely dominates in the swimming. It is not suitable for anguilliform type where viscous forces play the key role. Besides, it cannot be applied to the uniform mode because the shapes of caudal fin and pectoral fin violate the fundamental assumption of slenderness. Nevertheless, elongated-body theory has been used regularly in swimming studies and in robot design for predicting propulsive force and efficiency [29, 37, 38].

7.2.2 Development

MIT developed the world's first biomimetic robotic tuna (*Robotuna*) in 1994. From then on, development of biomimetic underwater robots became a popular topic with the combination and advancement of biomimetics, mechanics, materials and driving systems, and many fish robots have been developed. For example, RoboPike and vorticity control unmanned undersea vehicle (VCUUV) from MIT as the improved Robotuna [24, 39, 40]; robotic fish inspired by the carp from Mitsubishi [41]; a robotic black bass with pectoral fin propulsion from Kato Laboratory at Tokai University [42]; the robotic fish UPF-2001 by the National Maritime Research Institute (NMRI) [43]; underwater robot with rigid tail from Michigan State University; Nanyang Awana NAF-I and RoMan-II using caudal fin and pectoral fin propulsion, respectively [16, 44]; snake-like robot AmphiBot by the École polytechnique fédérale de Lausanne [18]; snake-like robot HELIX-I of TIT; SSSA lamprey-like robot; underwater robot CUTTLEFIN with fin-based undulating propulsion by Autonomous Systems Laboratory at ETH Zurich [45]; FILOSE robot from Tallinn University; autonomous robotic fish in the London Aquarium from the University of Essex [19, 46]; robotic eel from the Methran Mojarrad group are exemplars [5, 15, 17, 20].

These biomimetic underwater robots usually use real fish as biomimetic objects with high performance. They are available and have various potential applications in the aspects of protecting the underwater resources from pollution, underwater rescue, observation of the seabed and other special underwater tasks. Among the above-mentioned biomimetic underwater robots, the propulsion methodologies are mainly by conventional motor mechanisms. The motor mechanism is simple, but lacks flexibility. The robots using motor mechanisms usually are of large size and heavy structure with rigid materials and complex control system [47, 48]. The propulsion is not smooth as the real creatures, and results in low swimming efficiency and flexibility [49, 50]. It is difficult to realize creature-like propulsion performance with good flexibility by this kind of robots.

7.3 Biomimetic Soft Underwater Robots and System Design Architecture

So far, the biomimetic approach has been used to design a soft underwater robot for operation in the unknown or complicated environments. Through mimicking a real creature, the functions of the soft underwater robots can be classified into

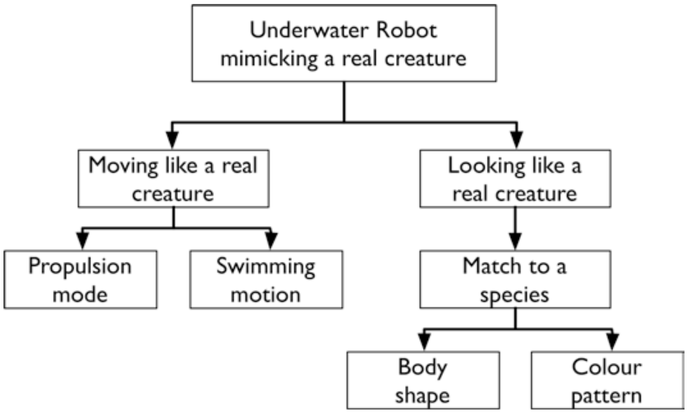


Fig. 7.1 Decomposition of functions for a biomimetic underwater robot

two types: moving like a real creature and looking like a real creature, as described in Fig. 7.1. For movement like a real creature, propulsion modes and swimming motions are focused on. In creature-like swimming, the performance criteria such as velocity, swimming number (the distance moved by per tail beat, related to velocity, frequency and body length), energy consumption, flexibility, adaptability, payload, are adopted to evaluate the motion performance. For looking like a real creature, matching body shape, colour patterns, etc., is implied. Colour patterns are composed of pigment-based and structural colour patches. It can signify the status of a creature or its motivation and can be used to communicate among species.

For the design of soft underwater robots by mimicking the real creature, an architecture is shown in Fig. 7.2. Frame members, body structure and materials, actuation mechanism, control system and buoyancy modulation, need to be considered in the robot design. The classification of propulsion modes for the biomimetic soft underwater robots is traditionally similar to that of real fish [5, 47, 51–56]. Based on the selected biomimetic creature's propulsion mode and corresponding swimming motion described in Fig. 7.2a [5, 51, 53, 56], the robot body structure is designed, with considering important factors such as robot's rigidity(softness), strength, stability, safety, payload, durability and so on. The suitable soft materials also need to be adopted in robot body design.

As for the actuation of the soft underwater robot, the appropriate actuation mechanism, such as by motors or flexible actuators with DC/AC source, should be adopted for desired robot performance. Based on the actuation mechanism of the soft underwater robot, the corresponding control systems are designed and constructed for its propulsion, including the communication system and driving system. In order to realize the dive motion of the soft robot, the buoyancy modulation needs to be investigated. The performance for orientation and depth of the dive motion for the soft robot should be evaluated. According to the various demands for soft biomimetic underwater robots in the underwater environment, different

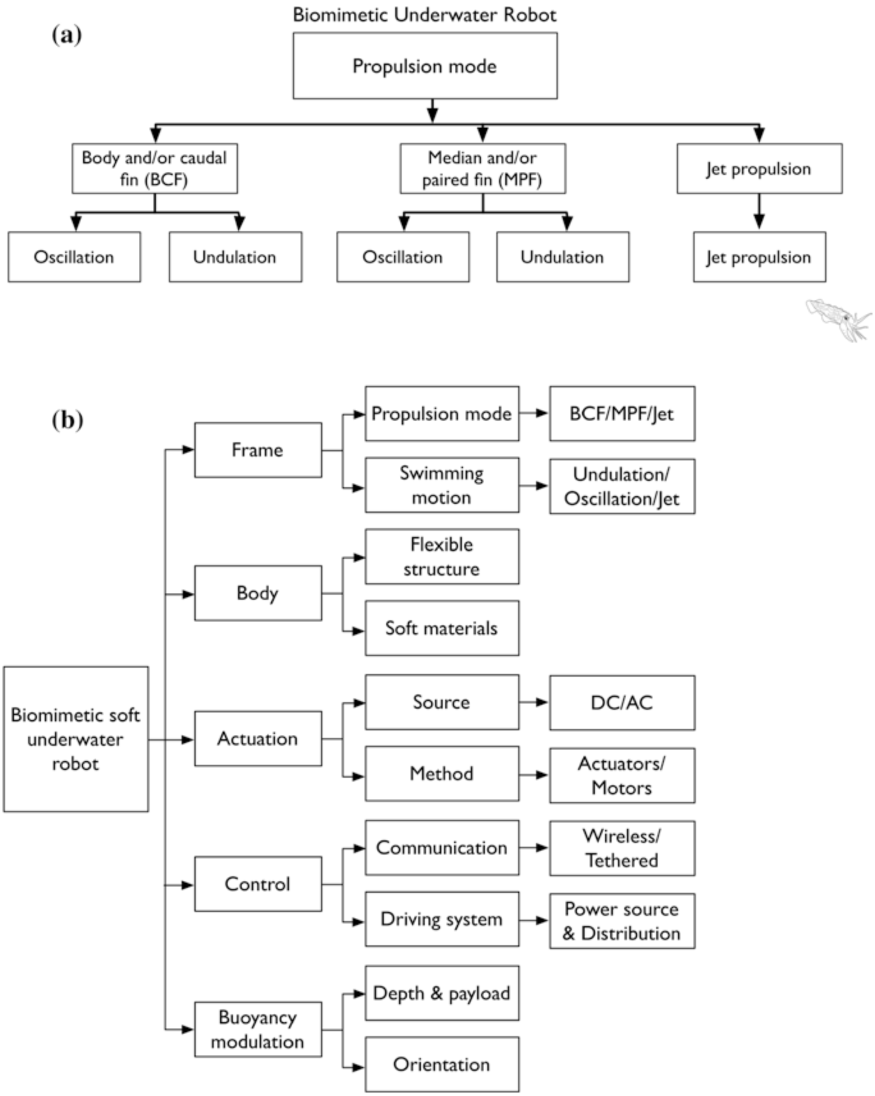


Fig. 7.2 Architecture for the design of a biomimetic soft underwater robot. **a** Propulsion modes. **b** System design architecture

components mentioned above can be highlighted to design the different soft biomimetic underwater robots for different functions.

In the design of a high-performance biomimetic soft underwater robot, biology, mechanics, hydrodynamics, control system and power source should be considered synergistically. In the mechanical domain, it is necessary to pay more attention to the robot frame, mechanical structure, soft materials and corresponding actuation components using biomimetic approach.

In the underwater environment, fluid dynamics plays the key role in robot propulsion and it is very important to investigate the hydrodynamic performance around the soft robot. It is necessary to utilize computational fluid dynamics (CFD) and flow visualization in the robot design as well as hydrodynamic performance evaluation. The vortex distribution in the wake around the robot has a great impact on robot propulsion and the wake dynamics must be considered in order to improve the propulsion mechanism to achieve a high performance.

Motion control and communication approaches are also necessary to achieve an optimal control system for the designed robot. High-performance sensors are also needed for feedback control and underwater navigation. For the power source, a power source with high energy density, high efficiency, high reliability and high safety is needed. In the long term, energy harvesting from the wave and the motion of the robot is necessary.

Generally, it is difficult to reproduce a creature-like motion using the conventional rigid mechanisms, and it results in low efficiency and mobility for propulsion [48, 57]. To solve the problem, it is very important to make the biomimetic underwater robots as soft as real creatures, including using soft actuators. Many biomimetic underwater robots use flexible actuators with smart materials for robot actuation, to obtain relatively better propulsion characteristics and motion performances similar to those of real creatures [50, 58–65]. In the early stage of the design of a biomimetic soft underwater robot using flexible actuators, most of adopted flexible actuators are ionic polymer–metal composite (IPMC), shape memory alloys (SMA), electrostatic film, PZT film or piezoelectric fibre composite (PFC). A comparison of characteristics of the flexible actuators is shown in Table 7.1. Among actuators, PFC actuator has larger output and faster response. And the propulsion mechanism using PFC actuator can be constructed to a simple and compact structure with high energy conversion efficiency and fast response based on high voltage.

However, in most research using such flexible actuators, only the feasibility of applying the flexible actuators to the biomimetic underwater robots to realize basic creature-like swimming motions have been considered. That is, how to achieve high motion performances of biomimetic soft underwater robots by design and control based on the essence of biomimetic soft robots is not emphasized in these works. A biomimetic soft underwater robot is intended to be soft and how to realize the efficient interaction between the flexible structure and the fluid inspired by biology is the essence of the biomimetic soft underwater robots.

Table 7.1 Performance comparison of typical flexible actuators

Item	Response	Durability	Environment	Output
IPMC	Fast	Good	Water is essential	Low
SMA	Slow	Good	Cooling and temperature control	large
Electrostatic film	Slow	Good	High voltage	Large
PFC	Fast	Good	High voltage	Large

Because biomimetic soft underwater robotics is a relatively young research field, new problems for different components and whole system are posed comparing with conventional theories and technologies of rigid robots in the underwater environment. Equivalent theories and technologies for biomimetic soft underwater robots have not yet been defined in a general form and researchers are still exploring new ways to develop the robots with high performance by trial-and-error method. In particular, the design and control methods for both mobility, stability and robustness with considering bioinspired compliance remain to be established. The requirements for shape, driving, controllability, path planning and sensing are complex and difficult in comparison with those for a rigid robot.

7.4 Proposal for a Numerical Simulation-Based System for Developing Biomimetic Soft Underwater Robots

7.4.1 System Configuration and Scheme

Development of biomimetic soft underwater robots is currently being carried out basically by trial and error and results in high cost for both robot development and performance improvement [66].

Some underwater robots have already benefited from design using available simulators [67, 68]. However, in the previous work on underwater robot development, robot design is carried out almost without utilizing the interaction between the flexible structure of robot and the surrounding fluid to realize propulsion performance by simulation [66]. Additionally, the control technologies of the designed robots are considered separately with the design of the robot [10].

In order to solve such problems, a design method different from that of previous work is proposed. It emphasizes the interaction between the flexible robot structure and the surrounding fluid based on a numerical simulation method and integration of the design problem with control problem.

Numerical simulation can consider the actual robot model including the mechanical structure with large deflection and the interaction with surrounding fluid effectively for performance estimation. Based on considering the interaction between flexible structure and surrounding fluid as well as the control input, the creature-like propulsion motion can be reliably established, and whether the design requirement is satisfied or not can be verified by the simulation results. The hydrodynamic performance and propulsion characteristics also can be identified and evaluated in the numerical simulation system by comparison with results of the experiment. The feasibility of the robot design can be carefully estimated through the numerical modelling and simulation analysis for final behaviour design and applications. When the desired propulsion characteristics and hydrodynamic performances are identified, the designed robot will be adopted as the suitable robot model for prototype fabrication.

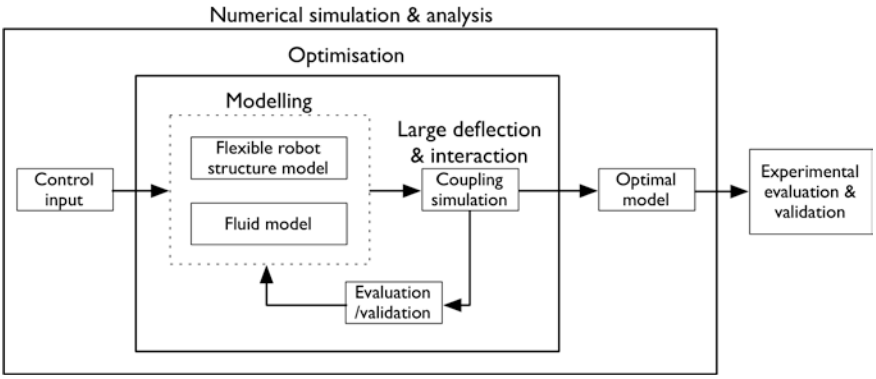


Fig. 7.3 Numerical simulation-based system for developing biomimetic soft underwater robot

A numerical simulation-based system, in which the interaction between the flexible robot structure and fluid as well as control input are taken into account, is hereby proposed as a necessary prerequisite for the successful design and development of the desired biomimetic soft underwater robot. Figure 7.3 shows the construction of the numerical simulation-based system for robot development. In the system, the optimal robot model is firstly to be derived through numerical simulation and analysis. Then the fabrication and experimental evaluation are carried out.

In order to develop a high-performance soft underwater robot using the biomimetic method, the creature-like propulsion approach must be determined based on different propulsion modes of real creatures. Through the designed propulsion approach, the modelling of the robot including the flexible structure, driving model and surrounding fluid is performed. Based on this robot model and control input design, the numerical coupling simulation considering the large deflection of structure and its interaction with surrounding fluid is performed to realize and establish the creature-like propulsion motion of designed robot, and then robot structure is optimized by established coupling simulation for performance improvement until achievement of the optimal model with desired performances. Through the optimization using coupling simulations, it can effectively obtain a relatively optimal model. When establishing the optimal model, experimental evaluation will be done by using an actual prototype. The detailed scheme of the design of a biomimetic soft underwater robot using the numerical simulation system is set out in Fig. 7.4.

Through design requirements of desired robot, an appropriate real creature is selected and referred to as a biomimetic object. According to geometric characteristics and swimming features of chosen real creature, the morphological and kinematic parameters are extracted to build the numerical model of the robot. Then, in terms of the requirements of hydrodynamic performance and manoeuvrability, the structural morphological parameters such as structural shape, stiffness and mass distribution, are determined initially through the numerical coupling simulation to

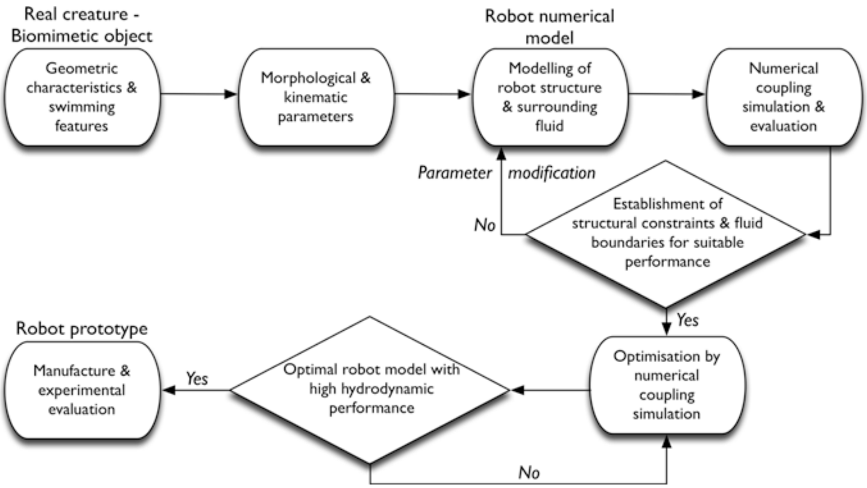


Fig. 7.4 Detailed schema for the design of a biomimetic soft underwater robot

derive the suitable kinematic parameters. Based on this initial robot model, modifying the parameters conditioned by both structure and fluid domain to design again for establishment of the structural constrains, control input and fluid boundaries until desired propulsion characteristics are realized.

Next, through the established boundary conditions in the structure and fluid domains and feasible control input, the optimization using coupling simulation is performed until an optimal model with high performance is achieved. Based on an optimal robot model, prototype fabrication and experimental evaluation are finally carried out.

It is possible to effectively develop the high-performance soft biomimetic underwater robot using this detailed scheme for robot design in a numerical simulation system. By the numerical simulation, numerical models can be further modified to improve the robustness and stability of motion due to environmental uncertainty.

7.4.2 Case Study: Development of a Subcarangiform Robot

Based on the method for designing biomimetic soft underwater robots mentioned above, a simple biomimetic soft underwater robot has been designed. Figure 7.5 shows the components of the robot. The fish type with BCF propulsion is regarded as the biomimetic object, and the subcarangiform swimming mode is adopted. In order to achieve the smooth propulsion and good flexibility, the flexible MFC actuator (a typical PFC actuator) is utilized to design the actuation structure of the soft robot. The corresponding driving system is also built to meet the requirements

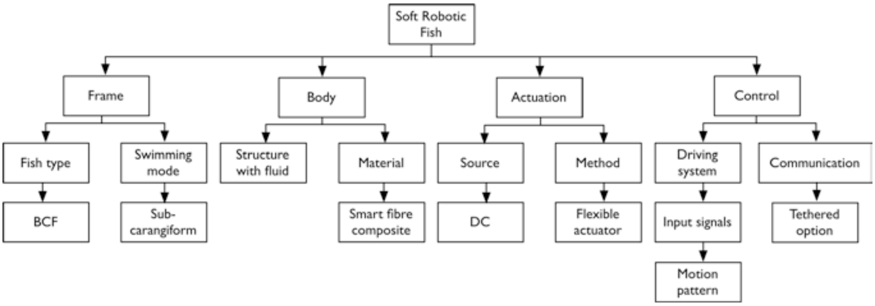


Fig. 7.5 Components of biomimetic soft underwater robot

of the flexible MFC actuator, including the control input design of basic signals. Based on the characteristics of the flexible MFC actuator, the carbon fibre-reinforced polymer (CFRP) is used as the main material for the robot body to realize desired deformation of the robot. Different with the conventional design method in which only the body structure is concerned, the fluid effect and interaction between robot structure and fluid are considered together with control input in simulation for design.

Using the proposed system and detained scheme shown in Figs. 7.3 and 7.4, respectively, the biomimetic soft robot has been designed and developed [69]. Figure 7.6 then shows the prototype of the designed biomimetic soft underwater robot and it will be called as new robot hereafter. A CFRP plate sandwiched by two MFC plates (M-8528-P1 type) is used as actuator structure for bending deformation. A weight made of steel is placed on robot head to increase the displacement of the tail end. A float is placed on the top part of prototype for balancing the robot in the liquid. The detailed specifications of the prototype are shown in Table 7.2. The epoxy 3M-DP460 is used to bond the MFC plate onto CFRP plate. The robot is put in a cubical fluid tank ($590 \times 133 \times 440$ mm) filled by Fluorinert Electronic Liquid FC-3283 with considering the high voltage driving of the MFC. For comparison, a robot developed in [70] is adopted and it will be called as old robot hereafter.

In the experiment a high-speed camera is used for observation and measurement of the robot motion. The driving system of the prototype is shown in Fig. 7.7. The control signal is generated by the computer and basic signal waveforms such as sine, square and triangle are used. A voltage follower between the high-voltage amplifier (AMP PA05039) and the computer is used to match the impedances. The high-voltage amplifier outputs -500 V to $+1500$ V to MFCs according to the control reference from the computer through DA board.

As the results of experiment, the new robot can realize various swimming motions in the fluid, such as forward motion, backward motion, turning motion, etc. The swimming velocities of the new robot and the old robot at different frequencies ranged from 1 to 30 Hz are shown in Fig. 7.8. The input voltage in

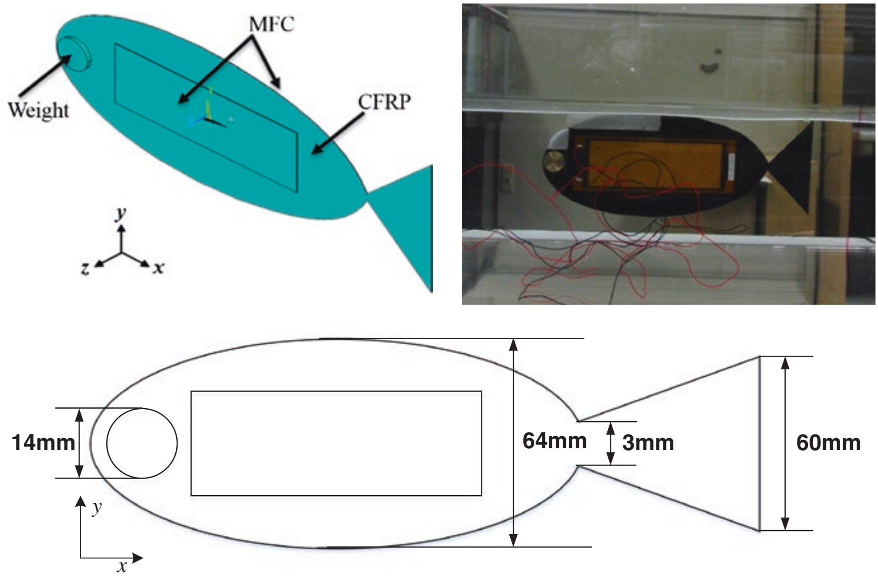


Fig. 7.6 Prototype of new robot

Table 7.2 Specifications of new robot

Item	Specification
Caudal peduncle height (mm)	3
Caudal fin height (mm)	60
Radius of head weight (mm)	7
Maximum body height (mm)	64
Type of actuator	MFC 8528P1 $\times$ 2
Actuator dimensions (mm)	112 $\times$ 40
Actuator active area (mm)	85 $\times$ 28
Body thickness (mm)	CFRP-0.2
Adhesive	Epoxy 3M-DP460

square waveform with the range of -500 V to $+1500$ V is applied on both actuators. From the figure, it can be known that the maximum swimming velocity of the new robot is 0.792 m/s at 25 Hz and it is larger than that of old robot (0.72 m/s).

In the biomimetic field, swimming number S_w of the fish is widely used to evaluate the swimming performances. S_w can be expressed by Eq. 7.7, where V is velocity, f is frequency, L is body length. Swimming number describes the distance of fish moved by per tail beat. The swimming number of the fishes is generally about 0.6 for high performances with good flexibility and mobility [71]. It can be utilized to evaluate the fish-like swimming performance of the biomimetic soft robots. The calculated swimming numbers of the new robot and the old robot at different frequencies are shown in Fig. 7.9.

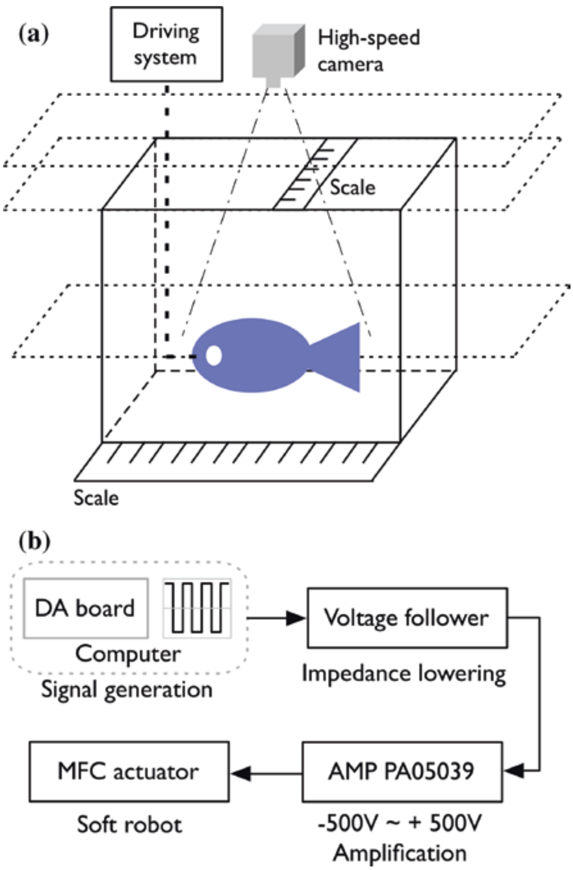


Fig. 7.7 Driving system of robot prototype in experiment. **a** Platform. **b** Driving system

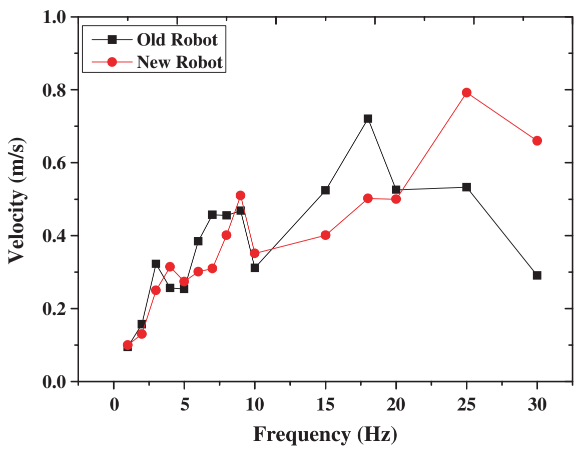
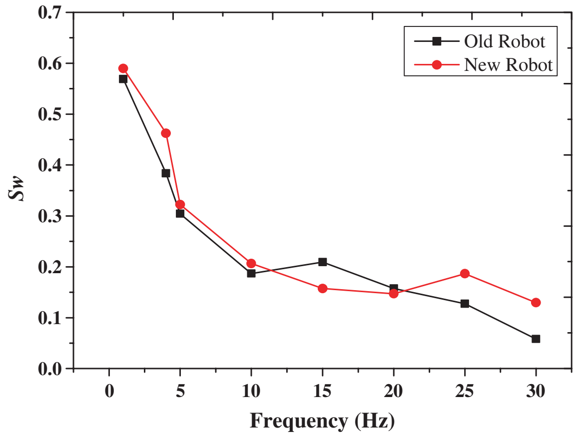


Fig. 7.8 Comparison of swimming velocities between new robot and old robot at different frequencies

Fig. 7.9 Comparison of swimming numbers between new robot and old robot at different frequencies



$$S_{\mathrm{w}} = \frac{V}{fL} \tag{7.7}$$

The swimming number of the new robot is larger than that of the old robot near the resonant frequencies where the first three bending propulsion modes occur (4, 21 and 29 Hz, respectively). Near the frequency of the first bending mode, the swimming number is 1.1 times that of the old robot. And it is of the order of 1.8 times that of the old robot near the frequencies of the second and third bending modes. The swimming number of the new robot is much closer to the value for a real fish (about 0.6) when compared with that of the old robot. Thus, it can be considered that the new robot shows the better swimming performance.

Turning motion of the new robot is realized by applying the input voltage signals with bias to the actuators of the robot. Figure 7.10 shows input voltage signals to actuators (both left and right actuators on robot body). The input voltage of a square waveform is used to achieve a larger turning velocity than that by sine waveform.

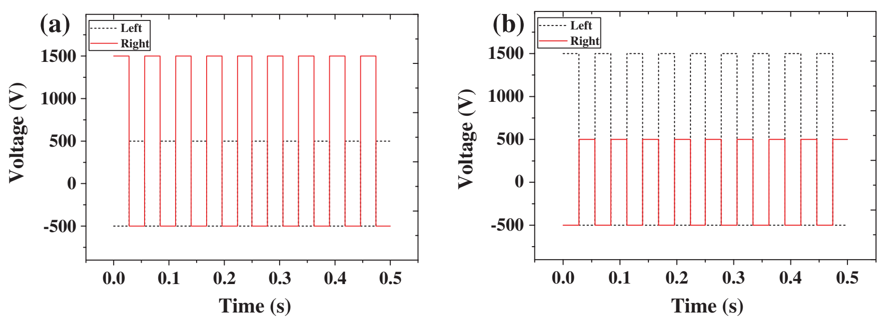


Fig. 7.10 Input voltage on both MFC actuators for turning motion. **a** Left turn motion. **b** Right turn motion

As a summary of the case study, a biomimetic soft underwater robot with higher swimming velocity and swimming number similar to that of real fish has been developed by optimization according to the design approach using numerical simulation system. It can be said that the design and control method by using numerical coupling simulation analysis is useful and can be applied to evaluate the propulsion performance of biomimetic soft underwater robots for further high-performance robot development.

7.5 Conclusions and Future Challenges

The design of biomimetic soft underwater robots is discussed in this chapter. Because most biomimetic underwater robots should adopt the flexible actuators rather than motor mechanism, the importance of designing the biomimetic soft underwater robots with high mobility, high efficiency and high adaptability is emphasized. Since the design and development of biomimetic soft underwater robots is a young field, theories and robotic technologies have not yet been refined into a general method and robot researchers are still exploring new means of achieving a new generation of biomimetic soft underwater robots.

The system design architecture for biomimetic soft underwater robot is presented, in which the biology, robotics, hydrodynamics, control system and power source are the main components to be integrated. In order to develop a high-performance biomimetic soft underwater robot based on design requirements and associated functions, a developing system including numerical simulation considering the interaction between structure and fluid as well as control input design is proposed as a necessary prerequisite for the design of a biomimetic soft underwater robot, because motion based on the efficient interaction between the flexible structure and surrounding fluid by adequate control input is the essence for biomimetic soft underwater robots.

Using the detailed design scheme in the numerical simulation system, the structural constrains, control input and fluid boundaries can be established and an optimal robot model can be achieved by simulation-based optimization. The environment uncertainty, different fluid properties, patterns of fluid flow and corresponding details should be considered in the numerical simulation system to improve robustness and stability. A reliable, stable and accurate numerical simulation system can accelerate the design process while realizing high propulsion performance.

However, the work up to now can be regarded just as a start point for designing biomimetic soft robots with high performance. Towards realization of full biomimetic soft robots with advanced performance as creatures or beyond creatures, the main challenges can be considered as follows.

1. From the view of biomimetics and biological evolution, biological structures such as brain structure, skeleton distribution and nervous system play key roles in realization of the behavioural features of real creatures. How to understand and achieve the cognition of such behavioural features and their evolution from

the biological structure of real creature is a new direction and challenge in the design of actuation mechanisms, control, navigation, communication and modulation through the neurology and cognitive science for the development of high-performance biomimetic soft robots.

Due to the great complexity of the biological musculoskeletal system of real creatures, the achievement and utilization of biological musculoskeletal distribution from a real creature through a biomimetic approach for desired creature-like motion have not as yet been realized. The related theories and design technologies have not been established in a general form. Future applications of soft robots significantly need a focus on adaptive behaviour design based on biomimetic approach during the motion design and control for unknown and unstructured environments. Also, there remains the question as to how to develop powerful and efficient artificial muscles and sensitive artificial sensors with high S/N ratio, another unavoidable issue in realizing biomimetic soft robots with high performance.

2. As the model for biomimetic soft robots, more complicated properties such as nonlinear characteristics, non-holonomic constraints, continuum–discrete conversion, etc., should be considered, because such properties are the dominant factors governing the motions of creatures and robots. Besides the important properties, the parameters for material property, soft actuators, etc., should be identified accurately because the parametric errors influence the motion of the robot in a more direct way when compared to the rigid robot. Further, although theoretically soft robots have infinite degrees of freedom, the number of actuators and sensors in practical soft robot is finite. Many degrees of freedom are not directly controllable.

   How to locate the soft actuators and sensors in the structure is another important issue in realizing controllable and efficient motions for the biomimetic soft underwater robots.
3. As mentioned above, a biomimetic soft underwater robot is a continuum with infinite elements and distributed actuators and sensors. And the robot is located in water, analysis based on simulation with considering the fluid and flexible structure interaction must be done for design and control of the robot. Numerical simulation is a useful approach for the simulation. But, how to realize efficient and stable motion analysis specially FSI analysis is a challenging issue for the future, because it is difficult to get stable solution while with huge computation cost by available software tools. Further, optimal design and optimal control based on the numerical simulations should be performed.
4. A new manufacturing technology for biomimetic soft underwater robots should be considered when designing the robots. Basically, the manufacturing technology for biomimetic soft robots is different from that of conventional rigid robots. For example, 3-D printing technology is a potential technology for fabricating biomimetic soft underwater robots, by embedding body materials, actuators, sensors, etc., together. To develop the biomimetic soft robots with high performance, precise 3-D printing and mounting technology capable of multiple materials as well as module parts is expected to be developed.

5. Another challenging issue is how to enhance the autonomy of biomimetic soft underwater robots. First, to realize the stable motion of the robots, internal sensors such as motion sensors are needed to define the state of the robots as necessary for the feedback control. Second, because the environment for underwater robots is more complicated and time-varying, such as the complex flow of water, many unstructured obstacles, sensors for recognizing the environment are also necessary to control the motion of the robot in that environment. Using the internal and external information from the sensors, self-stabilization, self-compensation, self-adaption and self-diagnosing similar to those by creatures are expected to be realized in the future.

The development of biomimetic soft underwater robots is a synergy technology of biomimetics, soft robotics, materials science, intelligent control, and sensing and communication technology. The technology is not only useful for developing underwater robots with advanced performance, but also can contribute to the breakthrough of general robotic technology. With the remarkable progress in related fields, it is believed that the high-efficient biomimetic soft underwater robots with high mobility, adaptability and autonomy can be realized in the near future.

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Chapter 8
Improving the Robustness of Mechatronic Systems

Antonio Lanzotti and Stanislao Patalano

8.1 Introduction

A system engineering approach seems to be effective in the design of mechatronic systems [1] and over time, dedicated rules have been provided for the application of such approaches to mechatronic systems design [2, 3]. Nevertheless, even if the approach has been continuously used over an extended period of time, there is a need for a revised methodological framework aimed to improve robustness of new mechatronic systems, with respect to both conceptual and operational vulnerabilities.

The lack of robustness at conceptual level is mainly due to a violation of design principles and a loss of knowledge. This lack is significant, especially in the case of new systems when the design choices, related to the architecture of the subsystems, have to be accomplished.

From the early development phases of new mechatronic systems, simulations can be performed to improve and optimise design [4, 5]. Sophisticated multi-physical models are, in fact, currently developed thanks to the availability of integrated environments for requirements specification, functional analysis, logical analysis and geometrical modelling [4]. The use of bond graphs to model the behaviour of systems characterized by subsystems operating with different energy domains is an effective way to represent mechatronics systems. Several contributions to this have been provided in literature [6, 7] and the existence of such contributions supports the modelling of mechatronic systems by this means, in particular to verify limits and constraints in their application.

The lack of robustness at operational level is mainly due to the underestimation of noise factors that can affect the performance of the system during the whole life cycle. Understanding the variation of the complex system is the critical point of robustness improvement.

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A significant issue within simulation activities is sensitivity analysis. The topic of modelling, simulation and analysis of mechatronic systems, oriented to sensitivity analysis, has been addressed in literature. El Fahime et al. [8] have studied the effect of variance related to dimensional parameters on the performances of a mechatronic system using a Monte Carlo simulation. Precup and Preitl [9] have presented a stability analysis method dedicated to fuzzy control systems with mechatronics applications. Further, the authors provide for the sensitivity analysis of fuzzy control systems with respect to the parametric variations of the controlled plant for a class of servo-systems used in mechatronics applications.

If we consider a pure mechanical system it is possible to locate different sources of variation. In fact, from a mechanical perspective we could consider dimensional variations (lengths and angles), geometric form and feature variations (position, roundness, angularity and so forth) and kinematic variations (small adjustments between mating parts). Therefore, according to a general architecture of a mechatronic system [10, 11] and the presence of multidomain and connected subsystems, it is possible to locate further sources of variation, related, for example, to sensors and intelligent computer control. In this context, the improvement of the robustness of a mechatronics system is an imperative need and research activities related to Robust Design (RD) in engineering [12–14] could make a concrete contribution to the design of mechatronic systems.

The aims of the chapter are twofold. The first is to highlight the issue of improving robustness of mechatronic system by working at conceptual level and operational level, respectively. The second deals with the adaption of RD methods to improve robustness of a selected mechatronic system, by working on operational level within an automotive case study.

8.2 The Methodological Approach

If we consider a mechatronic system we could refer to a general system architecture composed of a *mainly physical subsystem*, a *mainly sensor subsystem* and a *mainly control subsystem* [10]. In the following, by addressing the general architecture, the characteristics of two main levels aimed at tackling the lack of robustness are briefly described.

8.2.1 Tackling the Lack of Robustness at the Conceptual Level

Working with mechatronic systems architecture and the set of above-mentioned subsystems, several conditions appear. The system considered as a whole, in fact, could present coupled design parameters, redundant design parameters or,

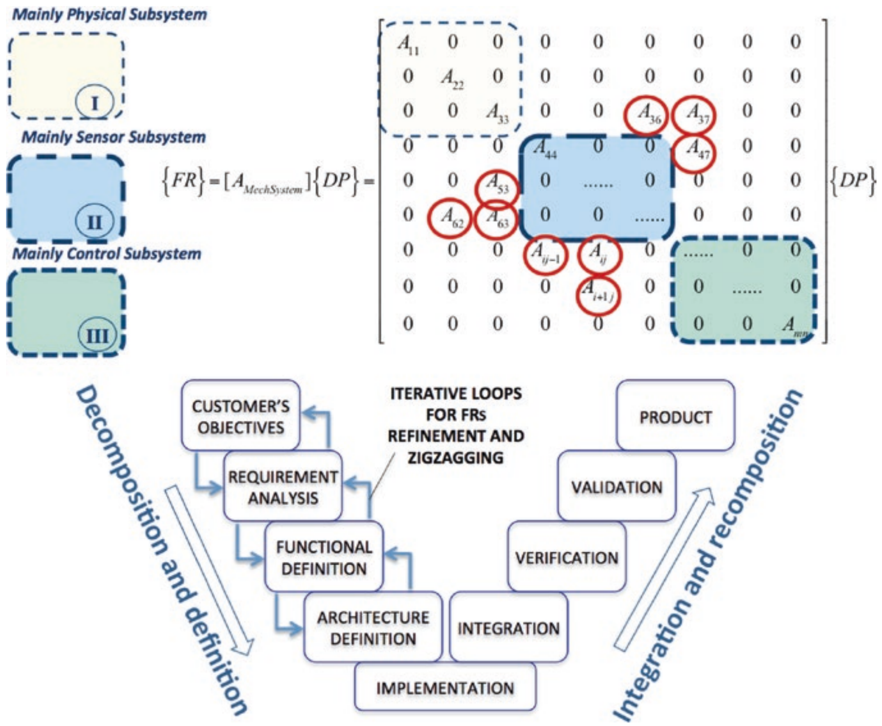

Fig. 8.1 Design matrix of a mechatronic system with coupled parameters (*top*); iteration of FRs refinements and zigzagging along V-model (*down*)

independent parameters. The last condition is the ideal one as stated by Axiomatic Design (AD) or by Axiomatic Product Development Lifecycle (APDL) [15, 16]. In such a condition, the Design Matrix (A) that represents the link between Functional Requirements (FRs) and Design Parameters (DPs) is a diagonal matrix. Otherwise, the other conditions state the non-independence of FRs (Fig. 8.1) and they require innovation on system architecture. In particular, design methods, as for example the TRIZ method [16–20], involving technical or physical contradictions, could be used and then the system architecture innovation could be accomplished.

The way to apply such methods is represented by the system engineering V-Model (Fig. 8.1). In particular, iteration from requirement analysis to implementation, moving along the "*decomposition and definition line*", could be used to accomplish the "*refinement of FRs*" and the "*zigzagging between FRs and DPs*", that are typical steps within AD [15].

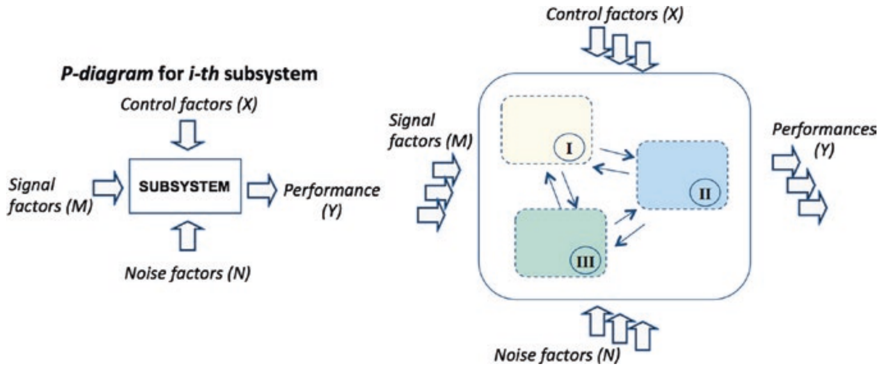

Fig. 8.2 P-diagram for the *i*th subsystem of a mechatronic system (*left*) and for the whole system (*right*)

8.2.2 Tackling the Lack of Robustness at the Operational Level

The robustness at operational level could be tackled by considering both for a mechatronic system as well as for the *i*th subsystem of a mechatronic system, a parameter diagram, i.e. *p-diagram* (see Fig. 8.2) and the related *Transfer Function*. In particular, the *Transfer Function* expresses the relation between *Control* plus *Signal Factors* and *Performances* under the effect of the *Noise Factors*, within the *i*th subsystem as well as the whole mechatronic system.

The relationship between the main components of a *p-diagram* and the components introduced by AD (FRs, DPs and A) is the following. DPs are translated into *Control* and *Signal Factors*; FRs are taken into account as *Performances* while the Design Matrix (A) is represented by the *Transfer Function*. Finally, *Noise Factors* are introduced as a perturbation related to DPs or external factors due to existing boundary conditions.

Working within mechatronic system design two main goals have to be accomplished. A preliminary one deals with the knowledge of the "*transfer function*" to be used. The transfer function could be: explicitly known (for example, function of real variables and differential equations), implicitly known (for example, continuous or discrete event simulation and numerical codes) or experimentally evaluated (for example, applying statistical approach or neural networks). An actual challenging field of research is how to define reduced model that can be used at the early stage of the design process of a new system instead of complete models that require highly intensive use of experimental resources [21].

A successive goal is the understanding of variations to accomplish the robustness of mechatronic system. The well-known RD methodology [22–24] is the starting point of the approach aimed to improve robustness at operational level. RD is a statistics-based methodology for improving the quality of a system by reducing the sensitivity of its performances to the sources of variation during its whole life cycle. Following that methodological path, after the system design phase that is discussed in the previous paragraph, the critical phase is the so-called "*Parameter Design*" phase.

The parameter design phase is aimed at identifying the main DPs, and to predict and evaluate their optimal settings. In this context, the attention is paid to improving system robustness, i.e. the system insensitivity to the variation due to noise factors. During the experimental phases, the design team can discover interaction effects never thought and consequently can increase his technical knowledge. Even if no "*discovery*" is attained, the experimental phase at least contributes to improve the knowledge of the design team. DPs are variables whose values can be still modified in this phase without any increasing of assembling or usage cost.

After that, the so-called "*Tolerance Design*" phase allows reducing the effect of variation allocating tolerances to parts in order to reduce the variation of the responses at the minimum cost.

The key steps of parameter design phase according to the RD methodology are as follows:

1. *Choice of experimental design strategy*
   Experiments must be accurately planned. An effective and technically viable experimental arrangement can be a cross-array [23] in which the "*inner array*" is defined by the design settings obtained combining control and signal factors and the "*outer array*" is defined by the settings of the noise factors levels. Each design setting of the inner array is experimented several times, as prescribed by the outer array. This is not the most efficient way to combine design and noise factors (see for example [25]), but it is the classical one and is the easiest for introducing the topic to engineers [24].
2. *Choice of DPs and levels*
   Design parameters depend on the system architecture and are defined during the preliminary design phase. It is interesting to understand at which extent they are singularly effective (main effects) on improving performance, but also to discover if there are synergistic or anti-synergistic interactions among these parameters.
   The choice of design parameter levels for an experiment is mainly left to the judgment of designers/engineers, who will consider technical and economical constraints (in the sense that the adoption of a certain design parameter level should not significantly increase the manufacturing or usage cost).
3. *Identification of noise factors and definition of levels*
   As already mentioned, the final objective of RD is to make the system design setting as insensitive as possible (i.e. robust) to the variation of internal and external characteristics, as for example part variation in their real parameters compared to nominal ones. So in general, the variation around the nominal value of each component of the system is considered as a noise factor in RD terminology.

For the definition of the outer array, more levels of the noise factor must be chosen. Obviously the higher the number of levels for the noise factor, the higher will be the representativeness of the population variation, but the higher will be the number of experiments to be performed in the virtual lab. So a compromise solution must be found. The most widespread choice for the definition of noise factor levels in the outer array is that proposed by Taguchi (see e.g. [22]) in which two or three levels are chosen. This problem is known as a discretization problem of a continuous distribution and many techniques have been proposed to improve the estimation of the "*weighted*" loss function [12, 26].

4. *Choice of the performance indicators* (*responses*)
   The responses for analysis are identified starting from the FRs, have a known target and are measurable. So for each case, the loss function can be chosen from among the classical ones or can be carefully tailored on the basis of the available knowledge. When more performance indicators have to be taken simultaneously into account, the problem moves from the univariate loss function to the multivariate case (see e.g. [14, 27–30])
5. *Analysis of the experimental results and definition of optimal settings of main design parameters*
   Experimental results can be analyzed on the basis of statistical methods. It can be a more or less standard analysis, depending on the adopted experimental arrangement and the degree of mathematical depth to be assured. Analysis of main effects and Pareto diagrams are useful and simple tools to evaluate the design parameters during explorative experimental phases [31, 32].
6. *If the final quality level is not satisfactory, it is necessary to skip to the tolerance design phase*
   The classical tolerance design is the last chance to fulfil the FRs in spite of variation but the smaller tolerance specification values, the higher are the production costs [33–35].

8.3 Model Reduction and Robustness Analysis for a Simple Case Study Concerning the Automotive Power Window System

The aim of the case study is to apply some steps of the methodological framework previously outlined to highlight actual and future research trends:

1. Development of the complete model to simulate the system acting as implicit knowledge of the transfer function;
2. Execution of an experimental phase for the identification of the reduced model through RSM methodology to simplify the task of optimal setting identification;

3. Generation and evaluation of optimal design choices by means of the reduced model taking into account noise parameters;
4. Validation of the results obtained by the reduced model through an experimental phase using complete model to verify optimal settings in order to consolidate robustness improvement.

8.3.1 The Power Windows System and the Related FRs

Power window systems are electromechanical devices used to lift and lower the car window. The main subsystems/parts of such power window systems are a DC motor, equipped with a worm gear, a sliding mechanism and a window constrained to move along rails. The DC motor–worm gear assembly is usually named a "*gear-motor*" while the sliding mechanism usually characterizes the architecture of the power window. When the command button is moved upwards or downwards, a voltage with direct or reverse polarity is applied to motor to drive the DC motor in the forward or reverse direction.

The motor drives a worm gear that operates Bowden cables[1] by means of a pulley. Then, the cable moves one or two supports and, consequently, lifts and lowers the automotive window. Usually, automotive power systems are single or double Bowden type when the cable shapes a single loop or double loop (cross cable), respectively. The present chapter deals with double Bowden power window systems.

The FRs of the power window system that have to be assured, during the usual development process of a new car, are the following:

FR_1—the window must complete the stroke in a fixed time;
FR_2—the sliding guides must support the window weight;
FR_3—the power window system must fit the available space within the car door.

In particular, the present chapter will address FR_1 as the user perceives the window stroke time as the main response of the system.

8.3.2 Building Object-Oriented Complete Model of the Power Windows System

Simulation of a power window system could be accomplished using Object-Oriented Modelling (OOM). Here, the modelling is accomplished by firstly providing a series of levels of detail as in Fig. 8.3. The power window system is

[1]A Bowden cable transmits mechanical force or energy through the movement of an inner cable relative to an outer housing.

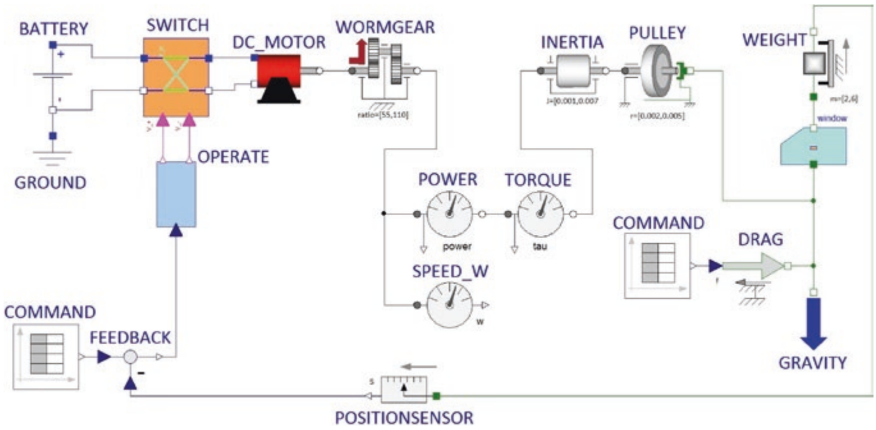

Fig. 8.3 Object-oriented model of power window system within Dymola environment

divided into three subsystems (*first level decomposition*) related to the control, sensor and physical subsystems, respectively. Such decomposition is also generally used when tackling the design of mechatronic systems. Each subsystem is then further decomposed according to functional groups using a *second level decomposition*. Finally, the third level decomposition is related to *generalised* components, components that characterize different physical properties such as component parts or torque and force vectors or signals.

A primary need is evaluating of how physical components affect system behaviour. Therefore, the model related to the physical subsystem is taken into account. As the power window behaviour is affected by the control system, the control and sensor subsystems are subsequently modelled and simulated by using the set of parameters defined for the physical subsystem.

The physical system is modelled using the Modelica language within the Dymola environment. Six objects compose the model as follows:

- *DC motor object*—this is characterized by three parameters: resistance, inductance and motor's torque constant.[2]
- *Gear object*—this is characterized by two parameters: speed ratio and efficiency. For a DC motor in a power window this is generally a worm gear with an efficiency value of the order of 45 %.
- *Inertia object*—this represents the inertia of all rotational components.
- *Pulley object*—this is characterized by pulley radius.

[2]For a DC motor it is possible to define k_T i.e. the motor's torque constant and k_b i.e. the motor's back electro magnetic force (emf) constant. In SI units k_T and k_b are expressed, respectively, in (N m)/A and V/(rad/s) and $k_T = k_b$.

Table 8.1 Design parameters for power window system

	Design parameters			
Gear	Speed ratio	Pulley diameter	Inertia	Efficiency
DC motor	Resistor	Inductor	Motor torque constant	Inertia
Sliding mechanism	Inertia		Friction	
Window	Weight		Stroke	

- *Window object*—this is modelled as a rectangular trapezoid without the double curvature of the window. Only the magnitude in the window movement direction is taken into account; window mass centre is computed by means of Varignon's Theorem [36].
- *Mass object*—this represents the window mass.

The power supply is modelled as a constant voltage generator of 13 V. At the beginning, no control on the evolution of the system is taken into account. The window stroke is equal to 0.40 m and is limited by means of source code and simulation stops when the stroke is completed. This allows the analysis of the system evolution without control system effects. The model of the power window system is shown in Fig. 8.3.

The model of power window system is characterized by a set of the design parameters (Table 8.1). A change of design parameters entails the variation of the lifting and/or lower performance as they produce the variation of a series of related or dependent parameters.

8.3.3 Model Reduction by RSM

In order to build an empirically reduced model for the main system responses, Central Composite Design (CCD) was adopted aiming at characterizing and optimizing the system. A CCD is an experimental design often used in Response Surface Methodology (RSM) to build a second-order (quadratic) model for the response variable. It contains an embedded factorial design with centre points which are augmented with a group of *star points* that allows an estimation of the curvature [37]. Within the set of independent parameters we define following subset of seven factors that are identified as the independent variable x_i (for $i = 1, 7$):

A—Window weight (x_1);
B—Speed ratio (x_2);
C—Pulley radius (x_3);
D—Inertia (x_4);
E—Motor's torque constant (x_5);
F—Resistance (x_6);
G—Inductance (x_7).

Table 8.2 Levels of the factors ($\alpha = 1.63$)

		$-\alpha$	-1	0	$+1$	$+\alpha$
A	Window weight (kg)	2.00	2.77	4.00	5.23	6.00
B	Speed ratio	55	65.59	82.50	99.41	110
C	Pulley radius (m)	0.020	0.026	0.035	0.044	0.050
D	Inertia (kg m^2)	0.001	0.002	0.004	0.006	0.007
E	Motor torque constant (Nm/A)	0.010	0.031	0.065	0.099	0.12
F	Resistor (Ω)	0.400	0.997	1.95	2.90	3.50
G	Inductor (H)	0.001	0.020	0.050	0.081	0.10

In particular, the *Efficiency* of gears and the *Friction* of the sliding mechanism (see Table 8.1) are here considered as constant parameters. As required by CCD, we determine factorial points (+1 and −1), centre points (0) and axial points (+α and −α). According to the characteristics of power window systems available on the market, it is possible to define the factor ranges in terms of alphas (+α, −α). In particular, such factor ranges represent a set of designing choices that does not imply significant cost variations. The values are shown in Table 8.2.

The full factorial plan is composed of 152 experimental runs. We carry out a fractional factorial plan of 50 experimental runs, using 6 centre points and 44 non-centre points. Here, the stroke time of the window Y[s] represents the FR_1 of the power window system to be assured. Therefore, stroke time Y is collected as main response during the present analysis. The results related to 50 experimental runs are briefly summed up in the following. In particular, the trend of stroke time is represented when the factors change.

ANOVA analysis, performed for stroke time Y (Table 8.3), highlights that three factors and one interaction are significant:

1. E—Motor's torque constant;
2. C—Pulley radius;
3. B—Speed ratio;
4. CE—Pulley radius and motor's torque constant interaction.

The model is significant and has an R-squared value of 0.91. The reduced model is:

$$y = -3.295 + 0.061x_2 - 10.08x_3 + 137.9x_5 - 2059x_3x_5 \tag{8.1}$$

Equation 8.1 can be used to predict the physical system response according to a given set of values. In particular, it presents an interaction between two significant factors (C and E). In the following, the prediction of system response, obtained by means of the Eq. 8.1, is compared with the one coming from the simulation of the power window system and obtained through the object-oriented model.

Table 8.3 Analysis of variance

Source	Squares	df	Square	Value	Prob > F
Model	288.66	35	8.25	29.10	<0.0001 significant
A—window weight	0.54	1	0.54	1.91	0.1887
B—speed ratio	24.96	1	24.96	88.06	<0.0001
C—pulley radius	45.50	1	45.50	160.57	<0.0001
D—inertia (transmission)	3.026E-003	1	3.026E-003	0.011	0.9192
E—motor torque constant	127.52	1	127.52	449.99	<0.00011
F—resistor	2.74	1	2.74	9.66	0.0077
G—inductor	0.045	1	0.045	0.16	0.6957
AB	0.20	1	0.20	0.70	0.4158
CD	1.871E-003	1	1.871E-003	6.603E-003	0.9364
CE	8.91	1	8.91	31.43	<0.0001
CF	1.122E-003	1	1.122E-003	3.958E-003	0.9507
G^2	0.10	1	0.10	0.35	0.5619
Residual	3.97	14	0.28		
Lack of fit	3.97	9	0.44		
Total	292.63	49			

Table 8.4 Data sets related to two system settings allowing a stroke time near to the target value

		System setting n.1	System setting n.2
B	Speed ratio	70	89
C	Pulley radius (m)	0.025	0.019
E	Motor torque constant (Nm/A)	0.041	0.021
A	Window weight (kg)	3.4	
D	Inertia (kg * m^2)	0.003	
F	Resistor (Ω)	1.5	
G	Inductor (H)	0.04	

The non-significant factors are the same for the two settings

8.3.4 Improving the Robustness of the System

Equation 8.1 is here used to address a preliminary result in terms of stroke time Y. Then, the simulation, performed through the complete object-oriented model, is used to accomplish the tuning of parameters. Finally, by addressing the noise factors it is possible to find the set of design parameters that makes the power window system robust.

By using Eq. 8.1 it is possible to identify two different settings of design parameters that allow a stroke time close to the target value $Y = 4$ s. Table 8.4 contains the data sets related to two system settings.

Table 8.5 Level assigned to noise factors

		Setting n.1		Setting n.2	
		−	+	−	+
N_A	Window weight (kg)	3.366	3.434	3.366	3.434
N_B	Speed ratio	69.3	70.7	88.11	89.89
N_C	Pulley radius (m)	0.02475	0.02525	0.01881	0.01919
N_D	Inertia (kg * m^2)	0.00297	0.00303	0.00297	0.00303
N_E	Motor's torque constant (Nm/A)	0.04059	0.04141	0.02079	0.02121
N_F	Resistor (Ω)	1.485	1.515	1.485	1.515
N_G	Inductor (H)	0.0396	0.0404	0.0396	0.0404

Table 8.6 Outer array for testing the setting n.1

Expt #	N_A Window weight (kg)	N_B Speed ratio	N_C Pulley radius (m)	N_D Inertia (kg * m^2)	N_E Motor's torque constant (Nm/A)	N_F Resistor (Ω)	N_G Inductor (H)	Y Stroke time (s)
1	3.366	69.3	0.02475	0.00297	0.04059	1.485	0.0396	3.96
2	3.366	69.3	0.02475	0.00303	0.04141	1.515	0.0404	4.03
3	3.366	70.7	0.02525	0.00297	0.04059	1.515	0.0404	3.97
4	3.366	70.7	0.02525	0.00303	0.04141	1.485	0.0396	4.02
5	3.434	69.3	0.02525	0.00297	0.04141	1.485	0.0404	3.96
6	3.434	69.3	0.02525	0.00303	0.04059	1.515	0.0396	3.91
7	3.434	70.7	0.02475	0.00297	0.04141	1.515	0.0396	4.11
8	3.434	70.7	0.02475	0.00303	0.04059	1.485	0.0404	4.04

With reference to the system setting n.1, stroke time Y is equal to 4.27 s while, by considering the system setting n.2 the stroke time Y is equal to 4.02 s. Then, by using the object oriented model of the power window system the simulated stroke time Y is equal to 4.0 s for both configurations. Therefore, the percentage error between the reduced model (expressed by Eq. 8.1) and the complete object-oriented model is 6.75 and 0.5 %, respectively.

It is then possible to apply the noise factors, as outer array, by taking into account two different levels assigned to each noise factor (Table 8.5). The two different levels are evaluated by considering the mean value and then by subtracting and adding the standard deviation. To simplify the analysis it is here assumed that the standard deviation, evaluated for each parameter, is equal to the 1 % of the nominal value.

Table 8.6 lists the outer array for the setting n.1, while Fig. 8.4 depicts the contribution ratios around the setting n.1. It highlights the contribution of the variation of each factor to the variation of Y. Similarly, Table 8.7 lists the outer array for the setting n.2, while Fig. 8.5 depicts the contribution ratios around the setting n.2.

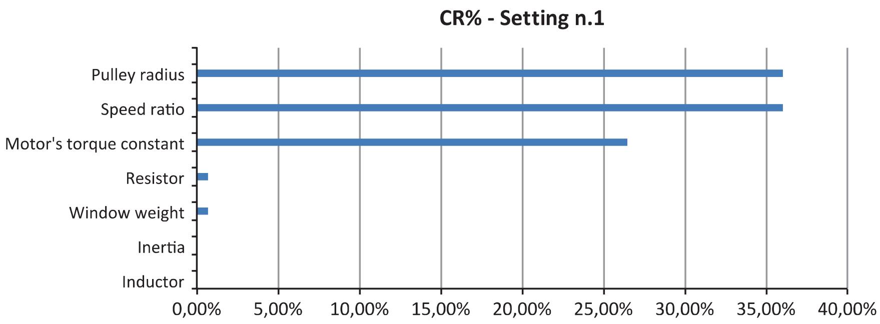

Fig. 8.4 Contribution ratios around the setting n.1

Table 8.7 Outer array for testing the setting n.2

Expt #	N_A Window weight (kg)	N_B Speed ratio	N_C Pulley radius (m)	N_D Inertia (kg * m^2)	N_E Motor's torque constant (Nm/A)	N_F Resistor (Ω)	N_G Inductor (H)	Y Stroke time (s)
1	3.366	88.11	0.01881	0.00297	0.02079	1.485	0.0396	3.97
2	3.366	88.11	0.01881	0.00303	0.02121	1.515	0.0404	4.02
3	3.366	89.89	0.01919	0.00297	0.02079	1.515	0.0404	3.99
4	3.366	89.89	0.01919	0.00303	0.02121	1.485	0.0396	4.00
5	3.434	88.11	0.01919	0.00297	0.02121	1.485	0.0404	3.95
6	3.434	88.11	0.01919	0.00303	0.02079	1.515	0.0396	3.94
7	3.434	89.89	0.01881	0.00297	0.02121	1.515	0.0396	4.09
8	3.434	89.89	0.01881	0.00303	0.02079	1.485	0.0404	4.04

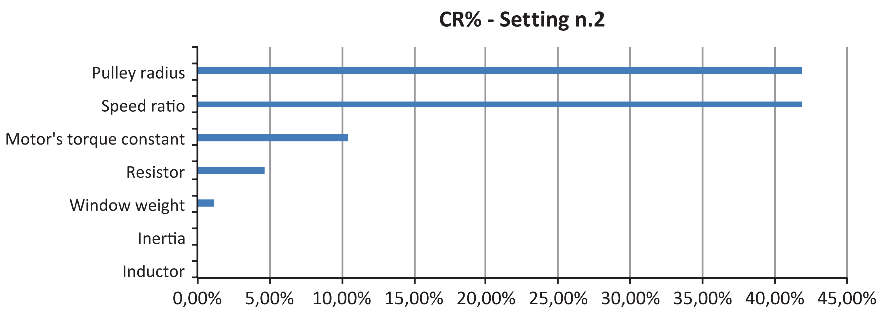

Fig. 8.5 Contribution ratios around the setting n.2

Table 8.8 Data related to performance indicators of the system

System setting #	Mean value	Standard deviation	Average loss	Signal-to-noise ratio
	y_m	σ^2	L_m	SN
1	4.00	0.062	3.89	36.15
2	4.00	0.050	2.46	38.14

Starting from the collected data concerning the effects of noise factors, it is possible to choose a more robust setting. The "*nominal is the best*" loss function can be assumed as follows:

$$L(y) = k(y - y_0)^2 \tag{8.2}$$

where $y_0 = 4$ and $k = 1000$. The average loss and Signal-to-Noise (SN) ratio could be written as in the following:

$$L_m = k[(y_m - y_0)^2 + s^2] \tag{8.3}$$

$$\mathrm{SN} = 10\log(y_m^2/s^2) \tag{8.4}$$

where y_m and s^2 are the mean and the standard deviation of the collected data, respectively.

The performance indicators of the system could be evaluated using the data in Tables 8.6 and 8.7. The results are reported in Table 8.8.

From these results, it is possible to choose the setting n.2 as the most robust setting that can be assumed without cost increment. So the quality can increase without increasing the cost, and this is the main aim of the RD methodology.

8.4 Conclusions

In the present chapter the issue of improving the robustness of mechatronic systems has been tackled. In particular, the need to operate at two levels (conceptual and operational, respectively) has been highlighted in order to accomplish first the mechatronic system architecture and, then, the mechatronic system design. According to the improvement of robustness at conceptual level the criticality is represented by the times to be spent, within iterative loops, to accomplish the diagonal form of design matrix, i.e. the set of decoupled design parameters.

According to the improvement of robustness at operational level, OOM and related simulations demonstrated to be a valid tool for the evaluation of system performances in presence of variability. Design of the experiments performed for the main performance of a power window system is able to address the most significant control factors. In this way, it is possible to locate the variations of control factors allowing the conscious choose of design parameters, among different system configurations.

This approach is addressed to the set of factors belonging to all subsystems (physical-, sensor- and control subsystems) of a mechatronic system and it is independent by its complexity. Therefore, even if further depths could be accomplished, this approach appears a durable way to improve the designing of such systems.

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Chapter 9
Integrated Manufacturing: The Future of Fabricating Mechatronic Devices

Nicholas Fry, Rob Richardson and Jordan H. Boyle

9.1 Introduction

This chapter explores current and future technologies for physically creating mechatronic devices, and in particular robotic systems. Robots consist of electronics, actuators and sensors within a self-contained mechanical structure and have the ability to exert controlled external forces to enable them to physically interact with the world around them. There is no doubt that robots have the potential to revolutionise many sectors [1], but there are many barriers to widespread use including public perceptions and difficulties in physically and computationally integrating robots into real-world environments. The cost of both designing and manufacturing robots is also very high. Improving manufacturing techniques for robots and providing better integration between the mechanical and electrical systems could help robots become physically robust, small, sealed, mobile and appropriate for the many challenging environments where their use could have a big impact.

9.2 Traditional Manufacturing Methods

Conventionally, mechatronic devices are created from discrete electronic, actuator, sensor and computation modules, integrated via a mechanical structure using bolts and other fastenings. The use of fastenings to secure all the parts limits robustness, as anything that has been assembled can also be disassembled [2]. The joints between components are common weaknesses, and as the device gets smaller the

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space taken up by these fastenings becomes increasingly significant. Assembly of these complex devices is also a big challenge; once a product has been designed, it must undergo a rigorous '*design for assembly*' process to make it suitable for manufacturing. This often introduces large costs and delays and greatly limits the designer. For example, the shape of a mechanical case must be simple enough that it can be released from a mould; circuit boards (both rigid and flexible) can only be populated when held flat and must incorporate off-the-shelf sensors in specific packages (physical cases) and footprint sizes (the size and shape of the component connector). Manufacturing processes dictate the way we design and produce items, imposing limitations on what is possible. We predict that advances in Additive Manufacturing (AM) will enable a new Integrated Manufacturing method that allows fabrication around mechatronic components. This could remove the need for post-fabrication assembly and the use of fastenings, yielding rapid production of robust devices.

9.3 Current Methods: The Rise of Direct Digital Manufacturing

Traditionally manufacturing was either manual, making it slow and labour intensive, or automated by simple robot operations, making it inflexible and costly to set up—requiring large product numbers to justify the expenditure. Computer control and digital design are helping to change the economic patterns that have defined manufacturing since the industrial revolution.

9.3.1 Automation

The design of a production line revolves around the need to make it as efficient as possible. Adjacent manufacturing operations should be located as physically close as possible and the movement of human workers and parts carefully choreographed to minimise wasted actions and time. While the philosophy behind assembly lines has not changed since they were introduced, the technology that powers them has, and it brings along its own set of advantages and challenges.

Through the application of sensors and actuators factories are becoming increasingly more automated. Where once a human worker had to load parts into a machine, a robot arm can now be coupled with a computer vision system that identifies a specific part and places it in the jig itself. This can increase the speed and efficiency of the process and is often safer, removing the need for a human to work closely with dangerous machinery.

For low volume manufacturing, Computer Numerically Controlled (CNC) machines are arguably having an even greater effect. The first CNC machines were traditional machine tools, such as milling machines and lathes, which were controlled by a computer. They have now expanded to include laser cutters, 5-axis milling machines and even 3D printers. CNC gives huge advantages as machines can quickly take a digital version of a part and turn it into a very high precision physical model. This disrupts the highly manual process that was traditionally used for small production runs, reducing the time and cost to produce parts while increasing the quality and precision. There is also an increased flexibility from the automation of these machines as changing the digital design file, changes the part being produced.

9.3.2 Additive Manufacturing

Additive Manufacturing (AM) is a disruptive technology that was first developed just over 30 years ago, but has burst into the public consciousness in recent years, as consumer desktop 3D printers become cheaper and more readily available. Additive Manufacturing and 3D printing are interchangeable terms to describe a range of technologies. The American Society for Testing and Materials (ASTM) International defines AM as "*A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*" [3].

There are different methods of depositing material in AM processes, but in all cases the first step is to digitally slice the computer model into thin layers. The layers are then physically laid down, one after the other, gradually building up a three-dimensional part. Thinner layers give finer detail, but also increase print time as more layers are required. Deposition technologies can be split into four broad categories [4], although the ASTM breaks these down further [3].

First there are extrusion-based machines. These feed semi-liquid material out of a moving nozzle, which then sets to form a hard layer. Many different materials have been used, including clay and chocolate, although thermoplastics are by far the most common, especially in consumer-grade 3D printers. These are commonly referred to as Fused Deposition Modelling (FDM) printers, although this is a trademark of Stratasys®. Various acronyms have been coined, but we will refer to this process as Fused Filament Fabrication (FFF).

Second, there are techniques that bind particles of powder together, either using glue or a heat source (e.g. a laser). In this method the part is constructed inside a vat of powder. To form a layer, an arm first sweeps a thin film of powder across the top of the print bed. The print head then traces out the contours of that layer and solidifies the powder.

Third is photopolymerisation, a term which refers to solidification of a liquid resin using a light source. Lasers, UV lights and even digital projectors can be used. Stereolithography (SLA or SL) was the first form of AM to be developed, and is widely used in industry due to its high resolution. An SL machine includes a vat of resin with a perforated build plate inside. At the start of a build the plate is

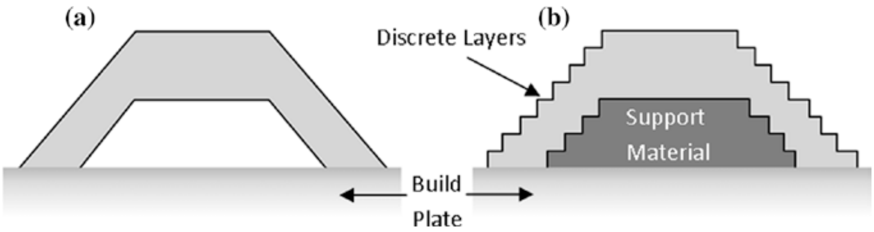

Fig. 9.1 Effect of layering, **a** subtractive machining yields a smooth surface, **b** AM part has a stepped surface and requires support material under the overhang

positioned just below the surface of the resin while a laser traces out the layer, curing the resin. The plate then moves down by the height of one layer and the resin either flows, or is wiped across, before repeating the process.

Finally there is sheet lamination, a process in which each layer is formed by cutting the shape from a thin sheet of paper, plastic or even metal. These sheets are bonded together using an adhesive or ultrasonic welding. The paper-based approach produces parts with poor mechanical properties, but can be combined with inkjet printing to give full colour models.

The layer-by-layer construction technique that is common to all these processes enables a new freedom in design as very complex shapes; even parts that cannot be manufactured using traditional techniques can often be realised using 3D printing (e.g. nested spheres). However, there are some limitations to the geometry of the parts that can be manufactured. The use of layers can cause a 'stair step' effect on curved surfaces (Fig. 9.1) as the shape must be digitised into discrete layers. Furthermore, each layer must be supported by a layer underneath, which means that any overhanging sections must be supported. Support structures are either printed in the same material as the part and designed to be cut, 'snapped' or machined off, or a different material is used that can be washed, peeled or dissolved away.

Although the impact of AM technology is sometimes exaggerated, it has undeniably had a dramatic effect on the way products are manufactured and will continue to do so. Since the Industrial Revolution, Economies of Scale have defined the structure of the manufacturing industry [5]. When a greater number of products are produced, cost per unit decreases. Unfortunately, this requires a large initial investment for manufacturing to become cost effective and therefore leads to large-scale, centralised, mass manufacturing. Due to the fact that AM requires no tooling or set-up, the price per unit levels off very quickly, and is often modelled as a flat line when compared with traditional manufacturing cost structures [6]. As Fig. 9.2 shows, this makes AM a very cost effective option for low-volume manufacturing. Currently traditional methods are more cost effective for large quantities, but the break even point will improve as 3D printers become more capable, cheaper and faster.

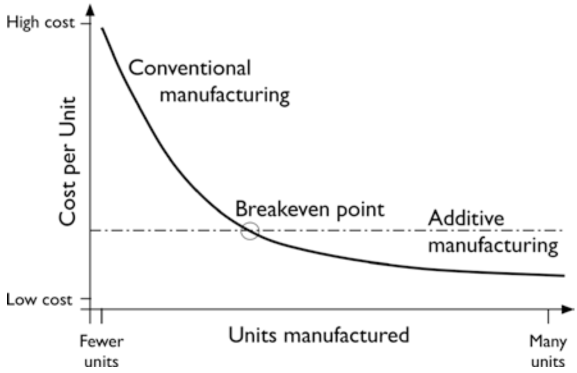

Fig. 9.2 A comparison of traditional and additive manufacturing cost models

AM will also significantly impact the Economies of Scope. This term refers to the fact that if one set of equipment, processes or materials can be used to make different products then the unit cost falls as the investment is split between more items [5]. 3D printers are extremely versatile in the geometries they can produce and there is little time or cost penalty incurred when swapping between parts. They can even produce different objects side by side on the build plate.

The abilities of 3D printers are so different from traditional manufacturing that they may allow new approaches to production that are not practical or possible with current manufacturing methods. For example, the layer-based process allows very complex geometries that could not be machined or cast due to object geometry limiting the access for tools or mould removal. Internal features can also be created, without the need to split the part into many pieces. This in turn leads to parts that can be lighter, require less assembly and have complex geometries, all while reducing material waste and lead times.

Additive Manufacturing was originally used exclusively as a Rapid Prototyping (RP) technology, as it allowed product designers to produce a physical model of their design within hours rather than days or weeks. Now, however, AM is expanding into Direct Digital Manufacturing (DDM). This is where AM technology is used to manufacture high quality, final production parts, rather than just prototypes. While the majority of 3D printers available are still aimed at RP, we are currently on the cusp of this exciting shift, where AM is being used to shorten supply chains, produce optimised parts and manufacture custom components. In fact, it is estimated that about 20 % of 3D printed parts are already for end use. Within 5 years it is predicted that this will be the majority, producing industrial tooling, individual components or full final products [4].

The rest of this chapter will focus on currently emerging technologies that will unlock the full potential of AM to revolutionise mechatronics manufacture. The far-reaching consequences of this revolution are explored in the final section.

9.4 Future Technology

9.4.1 Embedding Parts: Towards Non-assembly Structures

Joining components with fastenings tends to impose a set way of building mechatronic devices which relies on specific materials and fastening techniques and often results in a design which is inherently limited in terms of size, geometry and robustness [2]. The layer-by-layer construction of AM gives the unique opportunity to access the enclosed internal geometry of a part. This gives rise to the possibility of embedding components (motors, sensors, electronics) within object structures—to become an inherent part of the structure. This approach can confer major benefits when creating complex mechatronic systems.

Consider a humanoid robotic hand, for example. Researchers built two versions, the first of which used traditional assembly and included 60 parts (40 of which were fastenings) in each finger [7]. For the second version each finger was a single part manufactured using a hybrid AM method called Shape Deposition Manufacturing (SDM). SDM is a layer-based manufacturing method which involves a cycle of depositing material followed by precision shaping using subtractive methods. This approach allows different materials to be incorporated in a part, and even for components to be embedded inside the structure. Sensors were integrated into each finger, creating a reliable interface while protecting the sensitive electronics [7]. The joints and finger pads are made of a compliant material, while the link sections are a stiff polymer. This compliance greatly increases the robustness of the gripper; in fact the researchers have released a video of it being repeatedly hit with a baseball bat, with no resulting damage [8]. Researchers also selected the SDM process to mimic the impressive agility of a cockroach [9] and the climbing of a gecko [10].

The ability to make inherent joints is a key to simplifying assembly [11] and allows unique joints to be created. For example, the process has enabled ball and socket joints to be redesigned to limit their motion in certain directions by changing their internal geometry—something that is not possible using manufacturing methods other than AM [12].

Producing non-assembly joints (working mechanisms that require no assembly) is difficult; support material typically has to fill small gaps between parts [11]. Small gaps are required to give good tolerances for the joints, but this makes the support removal problematic. Traditional joints have been redesigned to result in close tolerances and simple support removal [11], but this work must be extended to enable a wider range on non-assembly joints.

Embedding inserts during the 3D printing process has given some interesting results, with components such as motors, circuit boards and gears being inserted to create, for example, a moving model of the stereolithography machine that printed the parts [13], a remote controlled buggy [12] and a robotic hand [14]. These inserts could also change the mechanical properties of the object. For example, metal could be inserted to increase the stiffness of a part.

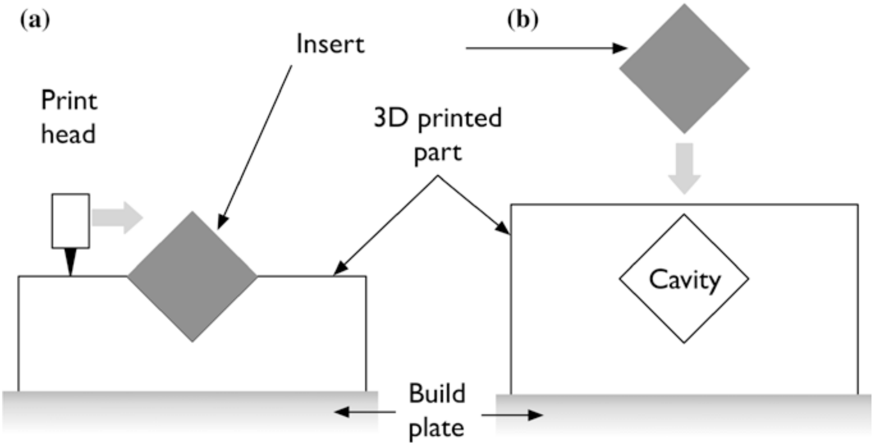

Fig. 9.3 Use of inserts in 3D printing, **a** print head collides with protruding insert **b** Insert cannot be embedded until the build is as tall as the insert, but by that point the cavity could be enclosed

There are challenges to overcome, however. Existing 3D printers are designed to work with planar horizontal layers, so the top of the part being built must always be flat to avoid collisions with the print head or recoating wiper arm (see in Fig. 9.3a). This requirement prevents the insert from being embedded until the build level is as high as it is. However, if the upper geometry of the part is convex, then the cavity will be enclosed by the time the build level is high enough to shield the component (Fig. 9.3b).

To overcome these issues, Shape Converters can be used (Fig. 9.4). These are additional parts that fit around the component, converting its geometry into one with vertical sides and a horizontal top that can be inserted without protruding [15]. These allow embedding but remove some of the possible advantages by adding extra process planning and assembly steps. The shape converter must be designed (it could have a complex shape) and manufactured, before being manually attached to the component for insertion into the main build. In more recent work, the ability to print using transparent materials has enabled printing around embedded optical elements to create displays and illumination, or even customised optoelectronic sensors [16]. This required infrared emitters and receivers to be embedded during the printing process. These were embedded by pausing the printer and manually inserting the component and a shape converter; the same labour-intensive technique that was developed a decade before [13]. The creation of fully integrated robotic mechanisms is being held back by a lack of suitable embedding processes that allow inserts to be seamlessly built around.

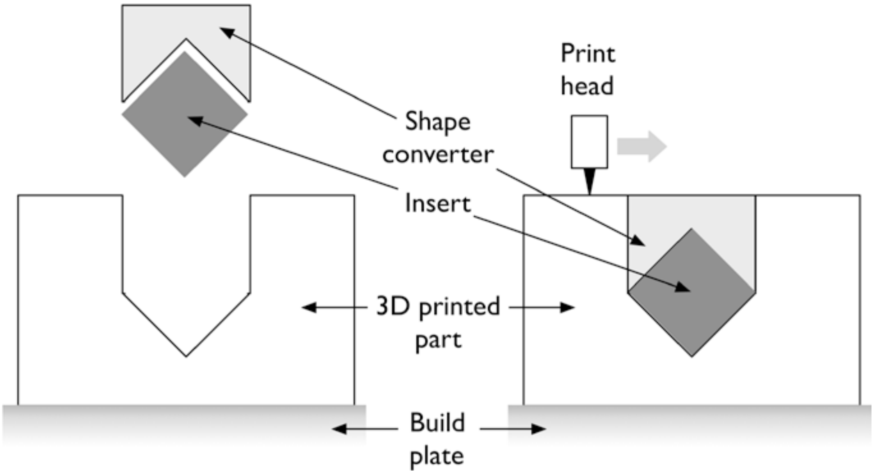

Fig. 9.4 A shape converter is assembled with the insert, converting the geometry to vertical sides and horizontal top, removing collisions

9.4.2 3D Printed Sensors

Including sensors, actuators and electronics in 3D printed structures will turn them into functional mechatronic devices. There is little reason to 3D print versions of parts that are easy to acquire and could simply be inserted, yet the integration and customisation potential of printing certain components does bring unique advantages that will be valuable in many cases. For example, a method to print speakers in any shape has been developed [17]. This allows the component to be totally integrated with the device it is in, allowing much greater design freedom, as the casing no longer needs to fit the shape of a standard speaker cone. By changing the shape of the speaker, the focus of the sound can also be adjusted [17]. A cylindrical speaker could be used to make an ultrasonic sensor capable of detecting obstacles all the way around a robot. Or a single object could have many individual speakers giving very directional sounds which could be used for artistic displays or communication [17].

The ability to print soft and transparent structures allowed researchers to develop novel optoelectronic sensors [16]. The electrical components can be situated near the surface of the part and externally wired to a control circuit, while sensing can be achieved using light signals channelled through printed optical conduits, avoiding the need for conductive material within the part.

By embedding infrared (IR) emitter and receiver pairs into a part, many different sensors can be made [16]. Using an Objet multi-material 3D printer, flexible, clear material can be used to guide the light [16]. Deforming this light guide changes the reflections, allowing movement to be detected. Switches, sliders, encoders and accelerometers have all been made using different configurations, for example a button is made by guiding IR light from the emitter to the receiver with a cantilever beam. When the user presses the button down it deforms the light guide, bending it away for the receiver. The receiver now registers a much lower signal and can be used to trigger a different electrical circuit. Using this technique customised, accurate sensors and user interface devices can be easily, quickly and repeatedly incorporated into any product [16].

9.4.3 Integrating Multiple Materials

Extending 3D printing processes to work with multiple materials opens up a huge range of possibilities for the technology, and while it is available for some methods, there are still challenges to overcome before this becomes a mainstream manufacturing technique.

The ability to combine different materials into one part would allow the mechanical and aesthetic properties to be adjusted. This can increase functionality as compliance could be included in different sections, or different colours or surface finishes could make AM more appropriate for final production runs as opposed to prototypes [18]. If materials with special properties, such as electrical conductivity, could be incorporated, then we would be much closer to an all-in-one process to fabricate functional mechatronic devices.

The Stratasys® Objet range of 3D printers are probably the best multi-material printers available at the time of writing [19]. They can be used to print parts with combinations of flexible, hard, transparent and full colour materials. The printer uses the Polyjet process, somewhat similar to that of an inkjet printer, in which tiny droplets of liquid build material are deposited from holes in the print head. The print head also includes an ultraviolet light that passes over each layer to cure it and solidifies the polymer before laying down the next layer. This jetting process means that different materials can be combined in a controlled way to create functional gradients of materials. In a process such as SDM each material is deposited individually with a clear interface between the sections. In contrast, Polyjet allows gradual material transitions that remove the weakness caused by a sudden change in materials. The material properties can even be precisely adjusted at different points throughout a model. This is an ability that is only possible with multi-material 3D printing. Adjusting the compliance, elasticity and damping of a part through its structure could have applications in many fields. For example, surgical devices may need to be strong and stiff in one section to aid handling or insertion while having a soft-end effector to reduce tissue damage. Achieving this with one integrated part would also facilitate waterproofing and sterilisation. In robotics, flexible joints actuated by shape memory alloy wire have been created, showing the potential of integrated non-assembly joints [20].

The Polyjet process, while giving many advantages, also limits the materials that can be used. As the polymers are cured using UV light, each material must be created to work in the printer, giving rise to Stratasys'® 'rubber-like' and 'ABS-like' descriptions of its materials. They share similar properties but are not the same as the traditional materials engineers are familiar with using. One of the biggest challenges, and opportunities, for 3D printing is increasing the range of materials that can be reliably used.

Malone and Lipson created the Fab@Home project, in which they designed a multi-material 3D printer that is open source and low cost [21]. They used this to demonstrate that using different materials and processes during a build they can produce working electromechanical devices. The system uses a syringe to deposit a wide range of liquid, gel or paste materials and a molten extrusion head to deposit thermoplastics and solder. This enabled the creation of flexible circuit boards, strain sensors, electromagnets, electromechanical relays, electroactive polymer relays and even batteries in different shapes. While creating functional electromechanical parts is a huge step for additive manufacturing, the Fab@Home system is low cost, low resolution and labour intensive, as processes must be carefully planned and the various materials are manually supplied to the machine. These components were functional, but cannot match the performance of their traditionally manufactured counterparts. Process planning is a difficult step as multi-material additive manufacturing gives new ways of making parts, so no set way of working has been established. This will continue to be challenging as different technical processes will affect the design and planning stage.

9.4.4 3D Printed Electronics

One of the most keenly awaited developments in AM is the ability to print electronics and conductive traces. This would enable functional mechatronic devices to be directly manufactured in one process. Novel designs that are not constrained by the need to include a flat-printed circuit board would be possible. Wires could also be replaced with conductive tracks, removing the difficulty of routing wires through complex and tight spaces and reducing the size and weight of the resulting device.

Batteries and transistors have been made via 3D printing [21], but there is a long way to go before these parts can compete with the efficiency and price of established processes. In the future many electrical components may be printed from their basic materials, allowing a huge catalogue of parts to be used without the need for each to be kept in stock. Despite this, merely printing conductive connections and inserting premade electronic components would still open up a huge range of possibilities. For the foreseeable future, at least, this will be the preferred method of incorporating electronics into an AM part as the mass manufacturing processes for electronic components are so well optimised.

The main options for printing conductive connections are: depositing conductive inks; extruding solder; extruding conductive thermoplastic filament or embedding wires. Commercial aerosol jet printers are available and have been demonstrated to produce a circuit on the wing of a UAV Model constructed via 3D printing [22]. The process uses a mist generator to atomise conductive ink, then aerodynamically focuses it, using a sheath gas, to create a fine flow. Feature sizes less than 15 μm are possible and the approach shows great promise for high-resolution circuits [22].

Conductive ink is used in a different way in the Voxel8 3D printer [23]. This is a high-end consumer 3D printer that combines FFF and pneumatic ink dispensing to create the first true embedded, 3D, electronics printer. The mechanical system is not particularly impressive here. Rather it is the material and control advances that are the keys. First, the ink they have created is an order of magnitude more conductive than others and, importantly, cures at room temperature. Second, through a partnership with Autodesk® they are offering a Computer Aided Design (CAD) program that enables circuit traces to be designed in 3D and for the printer to pause at the correct time to allow components to be inserted. Methods for process planning are still required, while design rules and best practice for laying out circuits in three-dimensional space will need to be explored.

Embedding wires is an alternative method of incorporating conductive paths into the AM build process and is appealing due the potential of low resistance, multicore or shielded wires, along with low cost. Wire is difficult to embed, however, as it does not directly adhere to the object and needs to be in tension to manipulate. Wire has been successfully embedded into a thermoplastic part by heating the surrounding material to soften it and pushing the wire just below the surface. Few technical details are available, however, and the effect on the surface finish has not been shown [24].

At a consumer level, FFF printers are the most common so there is great interest in conductive materials for this process. Researchers have used low melting point alloys, in the form of solder, as filament for FFF printers, which allows circuits to be printed [25]. This is cheap, readily available and can be used in unmodified FFF printers. However, it is difficult to control the feeding and cooling rates to give good results. There is much excitement around new conductive filaments that can be used in FFF printers. The filaments are made by mixing a thermoplastic, such as PLA with a conductive material. Graphene and nanocomposite materials have been shown to provide the best results but the resistance is still relatively very high. If short traces and low currents are used then functional devices and circuits can be successfully created using this method. An Arduino light sensor shield and single part flashlights have been printed, a simple robot has also been designed and will shortly be printed [26].

The fact that this conductive material can be deposited with the same process as the main build material simplifies the task of embedding the tracks within the part and means many printers will require no custom hardware. This will greatly speed the process of adoption. While these conductive materials are far from ideal and the resolution of FFF does not approach that of Aerosol jet or standard PCBs, the availability of this process to a large and inventive community will drive a rapid push in innovation as individuals attempt to solve a wide variety of problems and use it to manufacture their own designs. This will be unlikely to pose a threat to companies interested in using 3D circuits for a competitive edge; however they would be wise to pay attention to this unofficial research, as it is likely to be where novel uses and applications are explored.

9.5 Future Impact

While many individual experiments have confirmed the great potential for using AM to manufacture end-use mechatronic devices, combining these technologies is yet to happen. This section will look at the possibilities opened up by technologies such as embedding components and printing electronics along with challenges that engineers will need to face to realise them.

9.5.1 Fully Integrated Mechatronic Devices

If discrete components could be combined with multiple materials and conductive tracks, entirely new types of mechatronic devices could be created. Traditional motors and bearings could be inserted alongside integrated AM compliant joints, adding damping and robustness. Conductive tracks could connect actuators to a 3D printed battery whose shape has been customised to fit in the gaps between other components, allowing the device to be smaller. The conductive tracks could follow complex paths around the structure of the material, removing the need for a flat PCB and allowing wires to be protected. These tracks may then lead to a 3D printed socket allowing simple connections to different modules.

All of this would be integral to the mechanical structure of the device. Assembly would happen during manufacture, eliminating joints in the casing, clips that can snap or screws that could come loose. Removing the need for assembly could speed up manufacturing, reduce labour costs and help provide consistent quality. The monolithic structures that could result from fully integrated manufacturing would be ideal for harsh environments where toughness or sealing is important.

One must consider the whole life cycle of a product, however. It may be necessary to include access panels for maintenance and repair. Traditional inspection methods may be impossible so new processes will be required. Tight integration of multiple components and materials will present a particular challenge at the end of the product's life when the materials should be recovered and recycled. Some AM processes use materials such as thermoplastics that can be remelted, but others use chemical reactions that are not as simple to reverse.

While inserting components that are made in other ways is likely to be the most efficient method in the near future, it is possible that some components will benefit from 3D printing. Custom sensors, for example, may be a good candidate for Additive Manufacturing since modifying the shape to fit exactly where they are needed could be very useful. Or it may be that integrating basic but cheap sensors is best done through AM, while more complex parts are manufactured in an external process and embedded. This trade-off between the benefits of different manufacturing processes will have to be closely examined for each component to find the most efficient process.

9.5.2 Additive Mass Manufacturing

Mass manufacturing takes advantage of the economies of scale and allows large numbers of items to be made quickly and cost effectively. This is vital for companies who want to sell to large markets but this one-size-fits-all approach can result in a product which is not ideal for anyone. Additive manufacturing on the other hand takes longer to build an item but allows each unit to be personalised with almost no limits to the customisation available. It also allows geometries that cannot be made in any other way, opening up new possibilities for consumer products. The on-demand nature of AM is also a huge advantage. As businesses and consumers push for shorter and shorter lead times, the ability to speed up the production cycle has benefits in many sectors.

Combining the advantages of mass and additive manufacturing would create a totally new consumer environment. The way products are designed, fabricated and consumed would change. Products with mass appeal could be sold across the world; each one having the same underlying features, but with modifications to reflect the needs of the local market, or even the individual consumer.

Customisation not only affects the function and appropriateness of a product, but it can also add value emotionally, helping to increase the product's appeal to the user. Additionally, smaller markets that were once economically unfeasible could now be developed for, broadening the range of products available and giving manufactures wider market shares [27].

Google recently partnered with 3D Systems to develop a high-speed additive manufacturing machine to use for Google's modular smart phone Project Ara [28]. The machine 3D Systems have developed looks more like a mini production line than a traditional printer. It features 16 static print heads above a 'race track' where multiple build plates pass the heads at high speeds. This allows the machine to be able to deposit up to 4 billion droplets of build material in 1 minute, which made it 50 times faster than any other 3D printer at the time [28]. Unfortunately, the technology was not mature enough for Google to deploy so they are currently using a different method. Such abilities are still very much in demand however.

The Netherlands Organisation for Applies Scientific Research (TNO) has been developing a similar system that features 100 small platforms moving at 2 m per second under high-precision inkjet heads [29]. TNO have gone a step further than 3D systems and aim to incorporate other production processes including pick-and-place robots and surface-finishing equipment. This allows components to be inserted during the build process and for the system to make fully finished products. TNO claim that this facilitates the move from prototyping to manufacturing for AM.

While mass additive manufacturing will surely be possible in the near future, the systems discussed are still pilot systems. To convince manufactures to invest in this technology they must clearly demonstrate speed and cost benefits over current methods. Also, designing the machines to integrate seamlessly with current production lines and equipment is vital. Companies will not change their whole production method and equipment inventory just to facilitate the use of new technologies. When using AM for prototypes quality assurance and reliability are not so important, but for finished products the manufacturer must be confident that the process will be consistent and reliable, always producing parts that fit the specification. Despite the early stage of these systems it is inevitable that Direct Digital Manufacturing will eventually be used to produce a range of products, letting manufacturers respond quickly to consumer demand.

9.5.3 Designing Differently: The Integrated Design Process

Fully integrated manufacturing methods will require new design processes. Additive Manufacturing enables part geometry that could not be made any other way, be it moulded or machined, and frees the designer from considering the complexities of multi-part moulds or tooling requirements. However, the procedure is not yet as simple as just pressing print. The process planning step is still vital for checking if the design is suitable for AM. Currently designers often try to minimise the support structures needed to build a part, but the introduction of multiple materials and components will add further considerations. Engineers and designers must ensure there is a good dialogue as these new AM technologies are developed, ensuring that the effects of any design for manufacturing rules are reduced. Separate CAD packages are currently required for mechanical and electrical systems but this will need to change. It is important that user focused, intuitive software is developed alongside new integration technologies to enable the designer to consider a holistic mechatronic design.

Communication between the CAD package and the printer is also important. Since the mid-80s when the STL was developed by 3D Systems it has been the standard file format for rapid prototyping and AM systems. This specifies the surface geometry of a 3D object, but does not include any information on the materials, colours or textures used. This information is no longer sufficient for modern multi-material printers. To address this issue the ASTM has developed the Additive Manufacturing File Format (AMF). This is backwards compatible with STL, but also adds features such as being able to specify multiple materials, colour and geometry with higher fidelity. 3D printer manufacturers and CAD software developers must now take the lead and add compatibility to their products. The ability to create a streamlined workflow from conception to fabrication will be important for integrated design.

9.6 Conclusions

Additive manufacturing is making a huge impact in the manufacturing industry. However, only when it is combined with embedded parts, multiple materials and integrated electronics with its full potential to improve mechatronic and robotic devices be realised. AM removes the need to rely on the economy of scale and immediately gives a good economy of scope when manufacturing devices. Soon customisation will be available in a huge range of products and industries, which will be particularly important for robotics. There are many jobs that would benefit from automation and the use of robots, but creating a single mass market robot platform to meet these needs is still unrealistic, and small numbers of devices are expensive to build, limiting the market for robotics. If an enhanced 3D printing machine could be created that included abilities such as embedding functional components, printing joints and connecting electronics then customised robots, designed for specific applications would be much more readily available. This method of construction could also make the robots more robust which is extremely important for moving robots from laboratory-based experiments to real-world applications.

The process is also made cheaper and simpler, by minimising the assembly required, reducing material waste compared to subtractive methods and reducing the skills operators require. As 3D printing does not require long or expensive set-up, the lead times for parts could be greatly reduced. Combined with minimal assembly, on-demand manufacturing could be utilised in new applications such as in surgery (custom implants or tools could be created), or in search and rescue (a robot could be produced to fit a particular void or move on a specific surface). Combining these innovations could also be the next step required for self-replicating 3D printers, such as the RepRap project [30]. Currently, these printers can produce 50 % of their own parts (not counting nuts and bolts). Using the ideas of Integrated Manufacturing these fastenings could be removed and the progress in printing electronics may soon help these machines reach the goal of 100 % printable parts.

While it is clear that there is great potential for Additive Manufacturing, many challenges have been identified. Improved methods for embedding parts are a critical area that needs development, and printing electrical connections reliably with low resistance will be vital for mechatronic and robotic devices. Inherent issues such as discreet layers and the requirement for support material also need to be mitigated. Finally, combining all the technology together, with intuitive software and established process planning methods will finally bring about Direct Digital Manufacturing and Integrated Mechatronic Manufacturing.

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Chapter 10
From Mechatronic Systems to Cyber-Physical Systems: Demands for a New Design Methodology?

Peter Hehenberger, Thomas J. Howard and Jonas Torry-Smith

10.1 From Mechatronic Systems to Cyber-Physical Systems

Mechatronics may be defined as an interdisciplinary field of engineering science which aims to mutually integrate and interconnect mechanical engineering, electrical engineering/electronics and computer science (also often called information technology) such that the interactions constitute the basis for the design of successful products [1–3].

In a mechatronic design process the conceptual design phase is especially important. Here, the functional interactions between discipline-specific subsystems are determined, and therefore have to be carefully considered. This implies that during the phases of conceptual and preliminary design, the designer should be able to quickly and accurately evaluate those system properties that result from design changes in the mechanical components as well as in other components.

The successful development of complex mechatronic systems is only possible by close cooperation between specialists in the different disciplines involved. Thus the design activities take place in a multidisciplinary environment, which often involves engineers and other experts with different backgrounds [4]. In order to enhance the performance of new products, the positive interaction between different fields of mechatronics is increasingly being used. This may result in an increased complexity of the product because the mere combination

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of discipline-oriented partial solutions will usually not provide the optimal result attainable with an integrated system [5].

Mechatronic design emphasizes the integration between engineers skilled in specific domains such as mechanics, electronics and software. The interactions between product developers from these different disciplines are, however, often hindered by insufficient understanding between the disciplines, and by missing common platforms for modelling of complex systems [6]. As many sub-systems are sourced from external suppliers, there is a need for both horizontal integration within organizations and for vertical integration between the sub-system suppliers and the suppliers of the full systems. Lee [7] defines Cyber-Physical Systems (CPS) as the:

> …. integration of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.

Such systems can be found in areas such as aerospace, automotive, energy, healthcare, manufacturing, entertainment and consumer appliances.

For easy validation of requirements during the overall product development process methods are needed for the decomposition of high-level system requirements into criteria for design decisions. This will be an important aspect in the future, where new system architectures such as those of CPS are introduced [8, 9].

System modelling and evaluation are also important topics of CPS, for which improved tools and knowledge are always required by the engineering profession. In many cases, very accurate system modelling is not a reasonable approach to describing a complex system as the uncertainties and costs of even relatively detailed modelling may be so high that the drawbacks compared to simpler modelling become overwhelming, so there is increasing trend towards system-level models which allow a multidisciplinary engineering approach to be supported.

CPS system-level models need specific methods, languages and tools to support multi-view modelling in order to facilitate an interdisciplinary approach. More generally, this objective can be realized through multiagent modelling, based on an engineering cloud structure. This also results in the usage of tools supported by Model-Based Systems Engineering (MBSE) [10].

CPSs are often dominated by one engineering discipline. System-level models have to promote an equal treatment of all engineering disciplines involved during product development and project execution.

Figure 10.1 presents a structure model describing the relationships between mechatronic systems and CPS (shades of grey). These core elements are all comprised of a hardware element and a software element. The interactions between these can occur in the physical domain (e.g. clash between two robots detected, thanks to their sensors), or in the cyber part (e.g. dialogue between these robots supported by network protocols). The cyber part is then considered as the integration network. All these core elements are themselves made up of several modules represented by the small white boxes. The mechatronic systems and the CPS located on the border are then parts of the Systems of Systems.

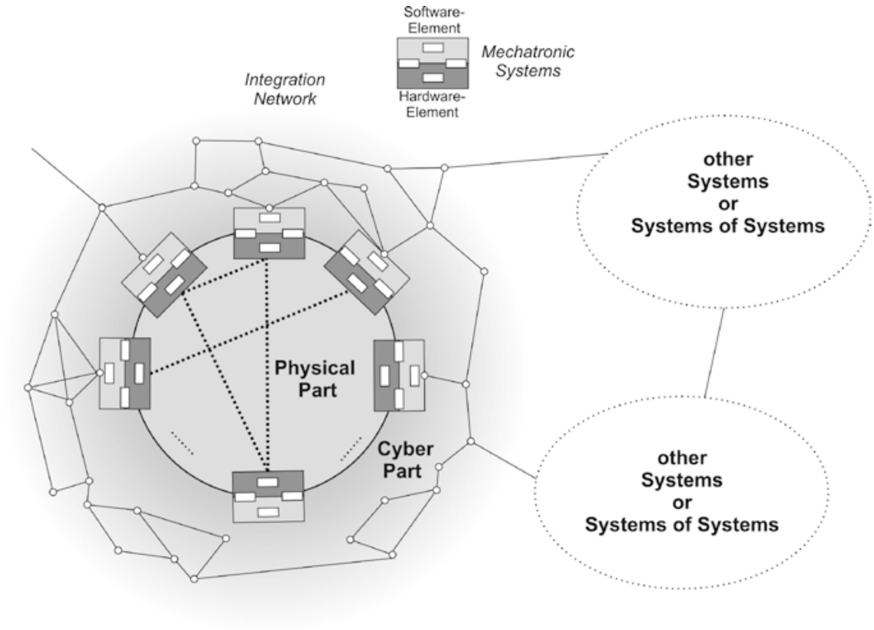

Fig. 10.1 Mechatronics and cyber-physical systems as a systems of systems [6]

10.2 System Design Methods

In this section the issue of system design methods is presented considering the hierarchy of systems and the used models.

10.2.1 Hierarchical Modelling

One of the major challenges in developing mechatronic products is the increasing function density and complexity of such products as well as of the corresponding mechatronic design processes.

The defining feature of mechatronic products, also known as systems of systems, integrated systems, or mixed systems, is that they merge solutions from disparate disciplines. As a consequence, a mechatronic design process must integrate multiple disciplines. There is a significant lack of such integration in traditional design processes which in general have emerged more or less from a single discipline and have incorporate other disciplines later.

The mechatronic design approaches (e.g. the V-Model of VDI 2206) focus on exactly this integration aspect of the synthesis, analysis and evaluation steps in modern mechatronic design. However, there are still a lot of open questions.

Hierarchical modelling concepts, i.e. the use of models with different granularity for different levels of abstraction, are a promising approach to model and master complex systems. The chosen approach is based on a modular structure of models (modular model architecture, model base, hierarchical structure of models) that allows for the configuration of system models from a library of sub-models and interface models. A sub-model can be a model of a single mechanical component or of a complex system, e.g. a model of an integrated mechatronic system including an embedded control system. An interface model represents the (physical) interaction between two sub-models, between sub-models and the system model or between the system model and (the model of) the environment of the system under consideration. This results in the advancement of reduced order modelling as a key for coping with models of complex systems, the improvement of the system view by system modelling and a significant advancement of the mechatronic design process itself by more systematic approaches with particular focus on the early phases of design (conceptual design, preliminary design).

The structure of the model of a CPS aims to store the product information from the entire product life cycle. This requires a hierarchical structure, which can be used in the early phases, which does not change during the product development process. Normally, product information is structured according to either the geometry or the assembly structure of the product. This results in problems in the early phases of the product life cycle as the geometry or assembly structure results from the development process and neither exists in the early phases nor is stable during the development process. The object which is most stable during product development is the set of resulting properties which define the product. As previously stated, requirements can change over time, but to be precise, changed requirements result in the definition and development of a new product. Trying to find a product information structure which is suitable for every set of requirements ultimately results in a structure which is identical for every product development process [11].

On the other hand, we have network of interactions and properties influenced by the different system elements. Basically, one type of property, a definable property, can be any property the designer defines directly (e.g. materials, manufacturing parameters, geometry). The totality of all definable properties then defines the complete product with all its properties and its behaviour.

The resulting properties are used to structure the generally high number of definable properties. This is done by assigning each definable property to the resulting properties influenced by this definable property. As previously mentioned, it is possible that a definable property influences more than one resulting property. For example, the definable property "*material*" influences the resulting properties "*maximum weight*" and "*maximum stress*"). A second level of structuring is achieved by assigning the definable properties to the different views. Each definable property can appear in a single view or in multiple views. For instance, the definable property "*material*" appears in the views "*producibility*" and "*costs*". In order to classify the definable properties in the matrix, a meta-information can be assigned to each of them. In most cases more than one model can be used for the description of a specific resulting property, whereas the less complex subsidiary models were used in the early phases of the product development process, when there is only little information about the product. During the product development process more and more complex subsidiary models can be used, to describe the interrelation between definable properties and resulting properties.

The knowledge about the interrelation between definable properties and resulting properties, gathered together from the subsidiary models can be used to set the values of the definable properties, such as geometric dimensions, material type, properties of the production processes. For example, the product designer uses a FEM model to determine stress.

10.2.2 System Model

During all phases of the design process there is a need to build models which may be seen as simplified representations of an original. In different phases these design models have different goals. During the conceptual design phase, physical principles, functions, structures, etc., have to be evaluated by executing models. In the context of mechatronic system design processes, the phenomena under consideration usually are of a physical or chemical nature. The models consist of a set of parameters as well as a set of logical and quantitative relationships between these models [4, 12].

The number of parameters increases from the conceptual design stage to preliminary and detailed design. According to the increasing degree of detailing during the design process, the granularity of the describing models becomes finer and finer, leading to a hierarchy of models as well as their describing parameters. For modelling and evaluation of solutions during all phases of the design process, we postulate models with different degrees of detailing (granularity of models) in correspondence with their describing parameters. The correspondence between models and parameters implies that the meaning of a parameter is well enough defined via its related model. Hierarchical models are very important tools for complex activities such as engineering design. Especially during the conceptual design phase where there is a high demand for models to describe the design concept with respect to the given requirements.

In addition to the hierarchical differentiation, the extensive functionality and complex structure of mechatronic systems has the result that it is generally not enough to optimize on a single criterion and a multi-objective optimization is often needed. Optimization separately within each domain will not result in the optimum system design. Therefore all the domains of, for instance, an automotive sub-system have to be treated concurrently, at least in the beginning of the design process. That way it will be possible to translate aspects from say the control or electrical design to the mechanical design at an early stage of the design process. This approach makes it possible to find a promising concept for the entire sub-system and not only for a specific domain within the sub-system.

In order to master the mechatronic design approach and to benefit from it as much as possible, a hierarchical design process is proposed in [11], in which the discipline-specific design tasks need not be integrated as a whole on the mechatronic level of the design task. Consequently, the system models should cover the different views on a system as well as the different degrees of detailing which lead from a hierarchy of models to a hierarchy of design parameters. Their description by significant quantities is used for analysing different mechatronic design concepts. The general requirements can be summarized as:

- Description of product information from all phases of the product life cycle taking into account the lifespan of a product as a necessity when storing the product relevant information within a single structure.
- Coupled analysis of different physical product properties as caused by the increasing integration of different applications and functionality in technical systems, the demand arises to find a uniform description of the various product properties, to define, describe, dimension, and calculate the product.
- Taking into account the view on an application domain as different development phases and mechatronic disciplines require different views on the object to be analysed. A general description of the requirement entails that model parameters should be provided in various combinations and different granularity for a further (more detailed) processing.

A major characteristic of mechatronic systems is that their properties are to a considerable extent defined by software elements. This initially leads to a shift from the physical function of the basic system to a realization through electronics or information technology. As a consequence, with some adaptations, intelligent systems of the future could include learning and decision-making abilities. Such systems may include, for example self-optimizing processes to adapt to changing conditions.

Crucial to the success of such a product is the behaviour of the overall system, as customer requirements and desires almost always relate to the whole system and not to partial sub-systems, components or even individual components. To assess the characteristics of the system it is appropriate to use models. For modelling and description of a mechatronic system, it is necessary to decompose the system into a selection of suitable subdomains, describing the boundaries of the considered mechatronic system to its system environment, enabling the flow of matter, energy and information.

The functioning of mechatronic systems is distinguished from other systems and hence requires the clear definition of interfaces and areas of responsibility. It must therefore be clarified in what way interactions with the system environment (e.g. chemical, energy, information) have to take place. In the ideal case, the whole system has the form of a cross-domain model. Unfortunately, the different disciplines use different modelling approaches and model descriptions. Moreover, within the disciplines, information and data at high detail level are only partially needed across the other disciplines. It is necessary to collect data for the overall behaviour for understanding of the overall relevance. The objective is to

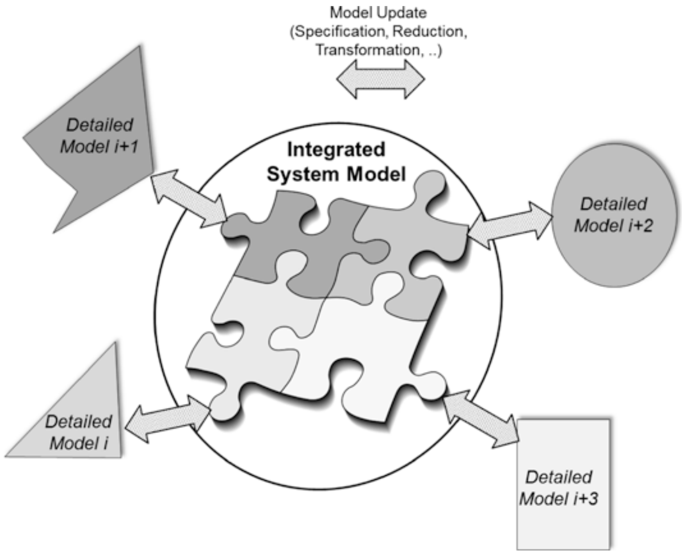

Fig. 10.2 System-level models [21]

create a system model with the information depicting the various domains, with focus on the importance for other domains. The challenge is that the knowledge of the entire system does not equal the sum of knowledge from the corresponding domains. The domain knowledge must therefore be generalized (abstracted) and integrated (see Fig. 10.2).

System-level models should at least facilitate management of existing data and visualization of both the relationships inside a system (between its sub-systems) and between a system and its environment. Additionally, they should provide the possibility to execute several simulations of load cases (test cases), thus allowing specific system properties to be evaluated. The simulations at the system level differ from those at the discipline level. Since simulations at the discipline level are usually conducted by highly skilled and specialized engineers who use particular, discipline-specific software tools, the simulations at the discipline level normally cannot be replaced by simulations at the system level. Therefore, methods are necessary:

- For modelling and simulation with special emphasis on the system view of the design object, i.e. the object under design.
- For conceptual and preliminary design relying on concept models at an appropriate system level representing the essential information including a significant system view of the design object.
- For the definition of modular structure of models (modular model architecture, model base, hierarchical structure of models) that allows for the configuration of system models from a library of sub-models and interface models.

- For the decision as to which information (e.g. which properties and which of their quantifying parameters) should be included in the system model and which in the sub-models.

10.3 Robust Design of Mechatronic Products and Systems

In this section the issue of robust design of mechatronic products is looked at, and several challenges are raised with respect to the differences in perspectives of the mechanical and electrical disciplines when it comes to reliability and robustness.

10.3.1 Motivation for Robust Design

Robustness relates to the ability of a product to perform despite unwanted variation to parameters and noise factors. Robust design is therefore an incredibly important methodology in mechanical design as it has the potential to allow manufacturing and assembly to have much looser tolerances, driving down the cost of production and increasing the quality of the product.

The benefits of having a robust design are not just limited to the relaxing of tolerances. In the news headlines and magazine reports, it is common to see stories of product recalls, high customer complaint rates, reduced product reliability, unscheduled maintenance and repair and even major or catastrophic product failure, all being damaging symptoms of a lack of product robustness.

However, this is the tip of the Iceberg! The reliability and quality issues that occur within a company due to a lack of robustness are large and costly. They include delayed product launch dates, misplaced RD resources, increased quality control and inspection and reduced innovation height.

While each discipline has its own approach to handling robustness, it is now very common for the effects of variation to run from one discipline through to the next, requiring robust design and optimization across disciplines, most typically from the mechanical to the electrical domains.

10.3.2 Robustness as Hidden Reliability

It is clear from interacting with the reliability engineering community, that the electrical engineers have a different tool sets and approaches to those adopted by mechanical engineers with regards to product reliability. However, there are some clearly overlapping methods.

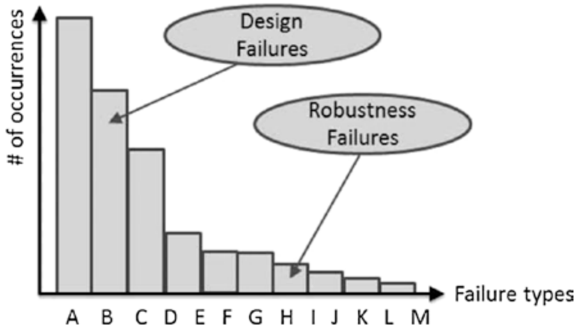

Fig. 10.3 Occurrence of failure modes [13]

For instance, Highly Accelerated Life Testing (HALT) is a methodology that can test the reliability of both the mechanical and electrical aspects of a design both independently and integrated into a system. HALT is used to test a single product (perhaps of nominal dimension) often in its intended use conditions, but with a highly accelerated use cycle. If we look at the nature of product failures in industry, HALT will only give part of the story. Figure 10.3 [13] is an illustrative example of the occurrence of the different failure modes. The failure modes with high occurrence (labelled design failures) are easily detectable through product testing such as HALT. However, the long tail of failure modes may occur perhaps only one in 100 or one in 1000 and may not be detectable during testing. These types of failures are termed robustness failures.

In addition to the above, it is clear that electronics reliability testing is dominated by Weibull analysis and mean time to failure. This is dominated by the more binary nature of electronics—it is working or it is not. Weibull would help to make a probabilistic failure analysis of components and therefore with a fault tree analysis (or similar) to calculate the probability of system failure at a given time.

In mechanical design, approaches such as kinematic design, design clarity [14], location scheme design [15], axiomatic design [16] are typical approaches to dampen issues when the product is not nominal (variation is present). The focus here is not to predict product life but to predict and decrease the change in performance due to variation. In an additional publication [17], 15 strategies for variation reduction are laid out. However, only two of these strategies (Quality Control and Shielding) are possible in the electronics industry.

10.3.3 Electrical Mechanical Interfaces

All electrical components have a mechanical interface to them. Mounting and fitting of PCBs is notorious for throwing up late stage issues and failures especially during the high volume ramp-up. There are two common errors here. First it seems to be a common mistake to overconstrain the PCB within the housing. An example

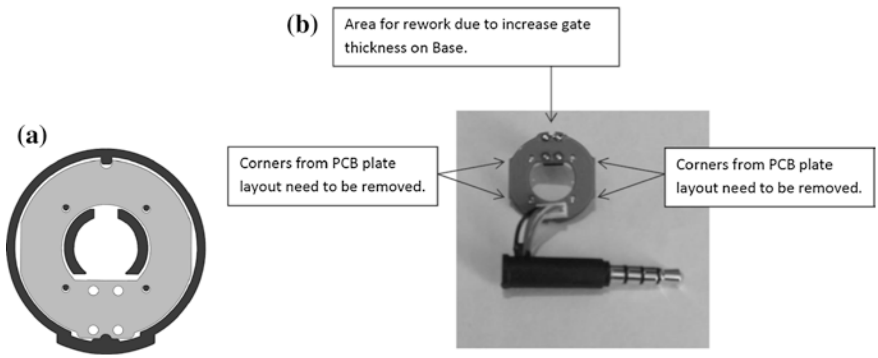

Fig. 10.4 Effect of overconstraint of PCB and housing. **a** Original design. **b** Redesign

of this can be seen in Fig. 10.4a where it is clear that there are too many surfaces responsible for the positioning of the PCB within the housing (the outer edge, the four pins, the inner edge, the notch at the top and the bottom). As a consequence the PCB had to be reworked in various areas before the assembly process—the areas of rework can be seen in Fig. 10.4b.

In the case above where a PCB is unable to fit correctly in its housing, the worst case will be time and money spent on rework before assembly. In some cases it may also lead to a potential distortion of the PCB during mounting, causing it some damage. When it comes to mounting of sensors, the positioning of the sensor can have a huge consequence on the performance of the product, this is a case of cross-domain robustness, dealt with in the next section.

10.3.4 Cross-Domain Robustness

With reference to mechatronics, cross-domain robustness arises where a variation in the mechanical domain leads to performance change in the electrical domain, or variation in the electrical domain affects the mechanical performance. There are many examples of this in various signal processing applications. One typical example can be seen in Fig. 10.5 where a series of teeth are arranged to rotate through a detector. The counting of the teeth by the detector determines both the speed of rotation and the position of the rotating part.

Figure 10.5b shows how the teeth are returned from manufacturing where the flash from the injection moulding introduces unwanted dimensional variation on the teeth, which means that the signal generated was less precise and may even reach a failure mode where a tooth is not recognized, producing a step change in the velocity reading.

The signal produced from the detector and the tooth arrangement in Fig. 10.5a is shown in Fig. 10.6. The signal processing software will then process the

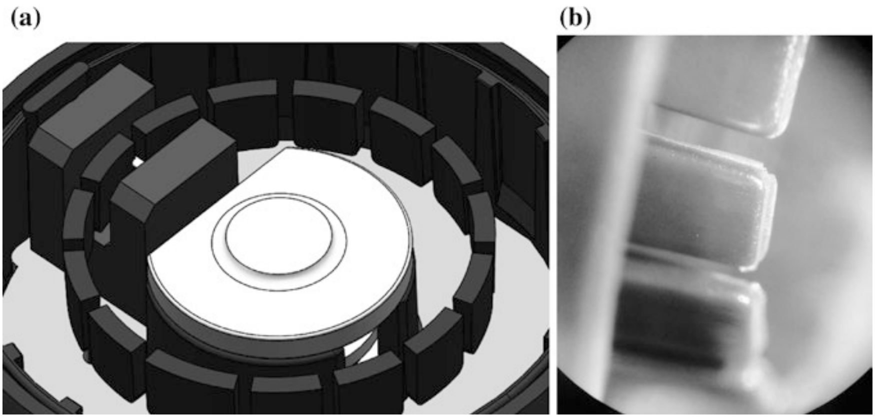

Fig. 10.5 Rotating speed and position detector. **a** Teeth and detector. **b** Detail of teeth

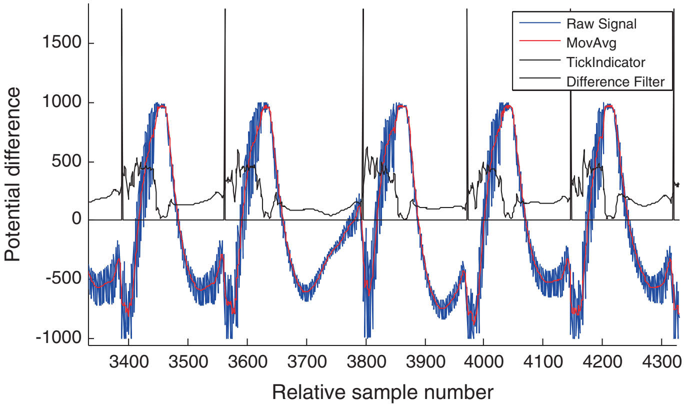

Fig. 10.6 Signal produced by the sensor of Fig. 10.5

differences between the peaks and the troughs on the signal in order to calculate when a tooth has passed the detector. However, at certain geometric variations and at higher velocities the detector can fail to identify the gaps between the teeth.

The above is quite a straightforward case where it is possible to do some simple robustness optimization so that the correct teeth numbers and dimensions are designed so that the detector works over a wide range of velocities. The robust optimization can also be undertaken for the microvariation of tooth dimension and detector positioning and even the influence of noise factors such as temperature causing thermal expansion. However, it is much easier for blind spots to occur between domains where is it unlikely that the mechanical engineer will fully appreciate the consequence of geometric variation on the electrical domain, and the electrical engineer will often be unaware of the potential sources of mechanical variation and the decisions that induce it.

This lack of understand between the domains is significantly compounded when the complexity scales up. Design changes and optimizations can occur in each discipline with not full appreciation of the effect on the other. A very good example can be seen in the following case.

10.3.5 Modelling Across Disciplines

While there have been many valuable attempts to model mechatronics from a number of different authors, the design and modelling of mechatronics is still a considerable challenge [18]. In product development, an incorrect product integration within a system is clearly seen in the media. For instance, in 2014 the GM ignition switch (see Fig. 10.7) recall was headline news, with record breaking costs/damages to the company of around $1.2 billion involving the recall of 28 million vehicles. The basic failure mode meant that the switch was unable to provide the torque to hold the key in the ON position while the vehicle was running, and in some circumstances the switch would slip from the ON to the (ACC)ESSORY position.

The failure to identify and remedy the issues in this case were quite systemic and reported at length by Valukas [19]. First, it is important to point out that this was a component provided to GM by a supplier and which had to fit on multiple GM vehicles. Both the switch and the series of vehicles each have their own electromechanical systems which must work in harmony. In the case of the GM ignition switch the mechatronic modelling approaches simply did not support the engineers adequately, leading to major consequences. The following three pieces of evidence are taken from the Valukas report to support this argument:

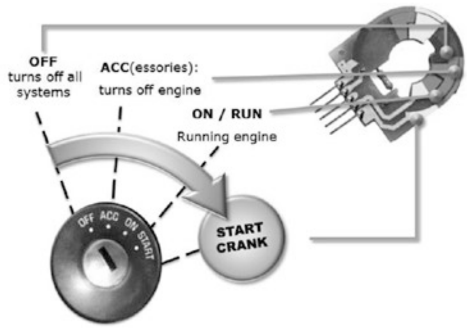

Fig. 10.7 Recalled GM ignition switch

1. None of the mechanical engineers working on the ignition switch were aware that moving the switch from the ON to the ACC position would shut off the airbag along with the power-assisted brakes and steering.
2. Due to electromechanical issues, the switch was sometimes unable to be operated in cold weather. This was then confused with the slipping issue.
3. Delphi had not achieved the required torque for the ignition switch. Given the switch's history of electrical failures, however, they were hesitant to make any changes that might jeopardize the functionality of the switch's architecture.

The first item mentioned in the report is about understanding the functionality of the products across domains. Without proper modelling of the functionality, engineers face the challenge of being able to foresee problems caused by decisions taken in one domain affecting other domains. This issue is not only present for engineers working on systems with many components such as cars, but is also present in products with fewer components and less complexity. The reason being that most companies are driving performance of their products in the pursuit of being one step ahead of their competitors. Inherently, this will result in many issues to be solved within each of the domains. Focusing on the problems lying ahead within each domain tends to attract engineers' attention to their own discipline-specific issues and away from integration issues; the so-called '*silo thinking*'. A failed interface between two domains may, however, just as well lead to a break down or degraded performance of a product.

The robustness of a mechatronic product can be affected in one of the three following ways:

1. Robustness issues within a single domain. For instance, feedback issues in electronic circuits creating unstable performance.
2. Robustness issues in the functional interaction between domains. For example, a mechanical strain gate creates an out of specification signal at one end of the performance spectrum, which creates an incorrect signal error when processed by the electronics.
3. Robustness issues caused by adverse effects. Adverse effects are unforeseen events creating an effect in domain other than where the event appears. Thus, heat from electronic components could cause a bearing to lock unintentionally due to the thermal expansion of materials.

To increase robustness, each domain must be internally robust (intra-domain robustness) as well as the product have interfacing functions between domains which are equally robust (inter-domain robustness). Some products may have a clear-cut interface between domains posing the opportune situation that the development can be divided into two different tracks with very little interaction (e.g. between mechanical and electrical development teams). The trend, however, seems to go in the opposite direction; namely to create more integrated products with many functional interfaces between mechanical, electronics and software solutions. This seems to have been the trend over the last decades and one might assume that this trend will continue in the future.

So to be able to create robust products in the future we need methods to access the inter-domain robustness as it seems that intra-domain robustness is better understood, modelled and comprehended, although not perfected. Tools to assess the level of complexity of the functional interfaces between domains as well as evaluating the vulnerability of a single functional interface and its effect on the robustness of the overall system are lacking. Fault tree analysis is one option but is far from adequate in assessing the robustness of a full-blown mechatronic system.

This speaks to the argument that the future for mechatronics research will respond to the modelling requirement to identify failure modes and the effects of variation across disciplines. A comprehensive modelling approach would lead to more effective design change management and design optimization.

10.3.6 The Importance of a Cybernetic Perspective on Robust Design?

In summary, it is quite clear that robustness optimization processes within a single domain, not only give an incomplete picture when optimizing a product, may actually reduce the cross-domain robustness for cybernetic products. This is not a minor consideration by any means, as the cross-domain robustness issues are seen as many both critical and main functions in many modern products. Examples of which are drone technology, self-driving cars, production robots or the exploding number of cybernetic products classed within the Internet of Things, all of which are characterized for a need of mechanical precision, timing and performance based on sensor inputs, signal processing. It would seem that defining cross-domain modelling approaches that can be used in conjunction with new and existing robust design approaches, not only defines the forefront of robust design research but also the quality and reliability of many emerging CPS.

10.4 Challenges for an Integrated Design Methodology for CPS

Design of CPSs involves close examination and further development of design methods, design processes, models and tools. The current trend in mechatronics involves networked mechatronic systems, or cyber-physical systems (CPS). Therefore product lifecycle management and product data exchange play an important role in CPS design. In order to push the performance of CPS and the related design process, it is necessary to increase the research on system modelling, thus significantly improving the system view. There are many challenges for future research towards improving the efficiency and quality of CPS product development. In terms of model-based methods and tools in early design phases which are the themes of a Design Society Special Interest group [20] who emphasize challenges related to the following topics:

- Methods to generate solution concepts for CPS.
- Methods for evaluation of solution concepts.
- Methods for early concept optimization.
- CPS modelling aspects in terms of model integration, modular modelling, and model interfaces.
- Performance of CPSs (multivariable key performance indicators, methods for cross-domain aggregation for performance evaluation).
- Methods and tools supporting CPS Design.
- MBSE for CPS.
- Integration of the cyber and the physical sub-systems.
- Cyber-physical robustness.
- Information and knowledge flow during CPS design processes.
- Modelling engineering change propagation and functional couplings in CPSs.
- Description and modelling languages for all design phases of CPS.
- Closing the gap between scientific approaches and industrial practice.

The key to an integrated design methodology for CPS is modelling and simulation (see Fig. 10.8). In this context design models and their interchangeability between different design tools are very important during the design process. From the mechatronic design process viewpoint, models are containers of the knowledge of the product during its total life cycle. Simulations are producing information of the design problem. This may improve product knowledge and potentially also the quality of many analyses and decisions. The presented approach relies on modular model architecture and enables innovative design, flexibility, speed and assistance in nonroutine design questions.

The main point of view of the work is "*simulation*", namely modelling and virtual experimentation regarding the behaviour of a system. The considered objectives of the simulation are:

- The creation of executable models of design concepts at the system level and the evaluation of alternative concepts.
- The creation and production of multidisciplinary simulation models at the system level of CPS.
- Simulation models for the use in system testing.

Linked to these objectives is the question of the required (mathematical) description of different types of simulation models. In this context, the aspect of usage and reuse of (simulation) models is an important topic. There is a lack of methods and software tools supporting the modelling and simulation aspects in the early phases of product development, during which detailed models due to incomplete information cannot be established and therefore the system has to be modelled on a level with high abstraction. It is a challenge for the future to derive the requirements for such tools and to develop appropriate software for this purpose.

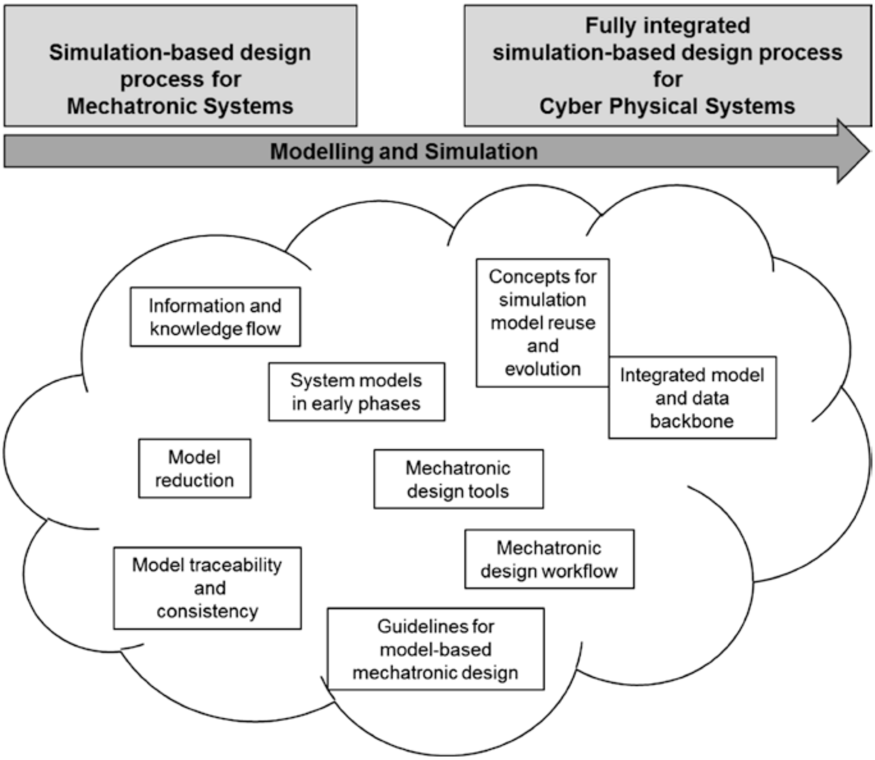

Fig. 10.8 Challenges for the future

For a simulation-based engineering approach, a model-based description of the system, with respect to its sub-systems, under consideration is a prerequisite. Especially for mechatronic systems this addresses:

- The models of the sub-systems.
- The integration of these models to an overall CPS—system model.

This engineering approach facilitates a holistic view on the overall system and should be continuously applied even from the very beginning of product development. Thus it becomes possible to model aspects such as requirements, functions, behaviour and structure in an integrated way which is essential especially during the early phases of design.

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Chapter 11
The Internet of Things: Promise of a Better Connected World

George R.S. Weir

11.1 Introduction

In recent years, progress in network-based applications has allowed a move beyond the staple asynchronous communication of email in which each party takes turns to compose and send a digital variation on traditional postal mail. Increasingly, synchronous (live) interaction between parties is possible through audio, video and typed digital channels by means of applications such as *Skype*, Facebook *Messenger* and Apple *Facetime*.

Although email remains a prevalent medium, users have also come to embrace social networking as a basis for selective broadcast and group interaction. These innovative applications are widely adopted across sectors, age groups and nations, in the take-up of laptops, smartphones and tablets. Of course, the increased use of networked devices reflects an associated growth in networking infrastructure. Wireless communication is normal practice in the use of mobile devices as well as a convenient basis for local area networks.

Increasing Internet use and the ready availability of connected information is often regarded as a natural step toward a greater degree of interconnectivity in which many of the devices in our homes, offices and factories become linked and capable of communication and control via local networks. In this chapter, we consider how the current context gives rise to the ideas behind the *Internet of Things* (IoT), look at how such extensive systems would function, and consider what benefits and disadvantages we may expect from such developments. As well as considering the present state of play, we will review the key ingredients, likely applications, ecosystem requirements, potential issues and prospects for a happy future enabled by IoT.

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11.2 Impetus

There are several factors in our current technological context that naturally direct developments toward the extended integration and enhanced data exchange that is core to the Internet of Things. On the one hand, there is familiarity with increasingly functional and immediate communication facilities, with the associated expectation that other information systems will be equally immediate and responsive. On the other hand, rising service costs are an impetus toward wider deployment of networked devices, since such developments are seen as a means to cheaper service provision and, especially, service monitoring. Thus, there is growing anticipation of integrated systems that afford greater convenience, new services and more economical provision of existing services. We may assume that '*A typical home will soon contain a network of gadgets designed to make life easier*' [1].

11.2.1 Government Initiatives

In the UK, a report entitled '*The Internet of Things: making the most of the Second Digital Revolution*' [2] was prepared by the UK Government Chief Scientific Adviser. In the USA:

> … the Federal government is working now to direct development and testing of such systems with an eye toward a variety of future applications. The US government calls such technology "Cyber-Physical Systems" (CPS) and is looking for ways they can be used to improve safety, sustainability, efficiency, mobility and the overall quality of life [3].

In a similar vein:

> The Singapore government has introduced a slew of initiatives as part of its goal to become the world's first smart nation, including a smart nation operating system, Internet of Things scheme targeted at homes, and pilot trials at a designated residential-business estate. [4]

Nations with developing economies are also rising to the IoT opportunity. For instance in India:

> One of the top most initiatives in the form of Digital India Program of the Government which aims at 'transforming India into digital empowered society and knowledge economy', is expected to provide the required impetus for development of the IoT industry ecosystem in the country" [5]

Each of these national perspectives reflects the view that engaging with IoT developments will enhance the welfare of the population and the economic benefit of the country. What then are the required ingredients for such progress in any nation?

11.2.2 Key Ingredients

The UK government report [2] identifies three key ingredients in the Internet of Things ecosystem:

(i) Communication;
(ii) Integration;
(iii) Data analysis.

First among these ingredients is the present and evolving communication infrastructure, comprising existing '*fixed*' network facilities, in addition to wireless technologies, such as Wireless LAN (WLAN), Bluetooth, GPRS (GSM) mobile telephony standards and anticipated new standards for '*near-field*' and close-proximity device interaction.

Integration is considered essential since the scope for IoT will depend upon the consolidation of diverse systems and standards, with '*local*' systems talking to each other and to '*upper level*' systems. Finally, data analysis appears in two roles. First, such analysis serves as a means of monitoring and managing the quality of interaction between devices (e.g. for fault detection), and second, as a value-added ingredient that provides insight on usage and performance. (e.g. for targeting bandwidth and premium enhancements). The expectation is that integrated systems will support widely distributed data gathering as well as centralised synthesis and analysis of data.

11.2.3 Applications

Within the UK government report, five core sectors are identified as having major potential to boost the UK economy through IoT developments

(i) Home automation
(ii) Agriculture
(iii) Energy
(iv) Healthcare
(v) Transport

For each of these sectors, we can anticipate IoT applications with significant economic potential. Home automation should have wide appeal and would apply not only to individual dwellings but also in the context of larger-scale building management systems designed to coordinate multiple interior systems, such as air conditioning, temperature and lighting. Small-scale automation facilities are already available for home use. These include '*smart thermostats*' that are network-accessible for remote control. Production and yield management in agriculture and other manufacturing contexts stand to benefit from the introduction of sensor-based feedback and automation.

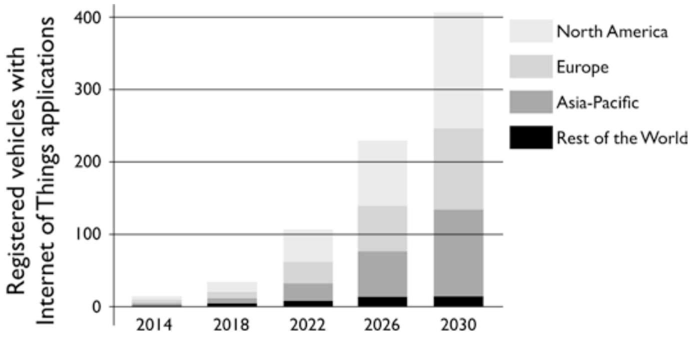


Fig. 11.1 Anticipated growth of in-car IoT applications (after *Smart Cars and the IoT* [10])

The energy sector has already shown movement in the direction of IoT through introduction of smart metres. These systems go beyond mere recording of total energy consumption to reporting consumption and usage patterns to the provider. Healthcare is an important application sector for IoT primarily from a cost efficiency perspective. The prospect of reduced cost health services through remote delivery (eHealth) is an eagerly anticipated economic boon for a presently overstretched and cash-strapped National Health Service.

In the transport sector government advisers predict significant growth in the use of in-car sensors, telemetry and inter-vehicle communication, as a basis for self-driving vehicles (Fig. 11.1). Progress in such smart transport is illustrated by the *Cooperative ITS Corridor*, an EU project to manage cars from Rotterdam via Munich, Frankfurt and on to Vienna [6].

Roads equipped with cameras every 100 m and WiFi antennas every 500 m, combine with short-range '*car-to-road*' communication, in order to measure the exact position of vehicles 10 times per second, within 1 m accuracy. Among the perceived benefits are improved flow management, such as addressing the '*braking shockwave*' problem on motorways, warning drivers of upcoming roadwork and other obstacles. Such initiatives also aim to harmonize smart-road standards among different countries. At first, such systems only employ '*car-to-roadside*' communication, with plans to extend this later to '*include car-to-car*' interaction.

While these anticipated economic benefits are central to IoT promotion by governments, we can already see relevant devices and technologies entering the marketplace that will contribute to the adoption and growth of IoT. The prevalence of home WiFi networks affords a convenient infrastructure for introducing the so-called '*smart*' devices with network communication capabilities. These vary from domestic appliances such as toasters and kettles, through wirelessly controlled light switches and multi-room digital music systems, to toothbrushes that report the effectiveness of their use through Bluetooth connectivity. In the home context, control facilities are readily afforded through mobile telephone apps or apps for Android and iOS tablets. These examples illustrate the potential integration of seemingly disparate systems.

In the realm of mobile systems, smartphones already support WiFi, Bluetooth and near-field connectivity. In conjunction with in-built GPS capability and suitable software applications, these phones can seamlessly interact with the local environment, registering their presence (or the presence of the telephone user), registering relevant localized data for presentation to the user and reacting to personalized settings or user preferences, based upon time of day and geographical position. Increasingly appearing as supplements to the ever-present smartphone, we find smart watches, fitness trackers and other wearable devices, such as clothes with in-built sensors. In keeping with domestic device development, these wearable devices build upon the functionality embedded in telephones and tablets to engage data processing and communication facilities. A case in point is the wearable PoloTech™ smart shirt from Ralph Lauren that measures the wearer's heart rate and respiration, distance travelled and calories burned, with data transferred to smartphone or tablet via Bluetooth.

11.2.4 Ecosystem Requirements

To appreciate the variety of prospective applications, we should consider the range of device types, the networking modalities and the methods of communication that are likely to comprise the essential infrastructure or ecosystem for the Internet of Things. One essential aspect of such technologies is the inherent flexibility that arises from multiple scales of device (with differing capabilities), different means of establishing intercommunication with other devices and a variety of alternative network topologies to suit differing needs. In terms of device capability, and associated scale, we may distinguish three device varieties, characterised by the roles that they play:

(i) Location markers (Passive).
(ii) Data gathering and relay (Active).
(iii) Decision-making (Active).

While we may naturally think of computation and data processing as necessary features of IoT devices, considerable utility can be added through the use of 'passive' objects as components within a local network. Such objects are passive in the sense that they have no native facility for generating, sensing or processing data. Instead, they are able to signify their presence through use of '*location markers*'. These markers may be based on Radio Frequency Identification (RFID) tags that can be detected by RFID sensors. Such '*smart labels*' may be battery-powered and actively send their ID by radio waves or simply wait to be read by an active RFID reader. The sole purpose of such tags is to signify the identity and presence (location) of the objects to which they are attached. The objects and the tags may be passive but detectable by other active systems. This allows for detecting or tracking tagged items and transfer of such information to local or remote computers.

The second variety of device has the native facility to capture and relay data. This requires some sensor capability but, while in this sense active may have little or no data processing capacity. The principal role for these sensor-based devices is to gather local data and relay this to other more sophisticated devices where the data from multiple sensor devices will be collated, aggregated and, perhaps, analysed. Our third variety of device covers those that actively process received data. This includes any active device that receives sensor information directly or indirectly, via other sensor systems. Combinations of these three device varieties support a hierarchical structure that allows data to be passed '*upstream*' from multiple sources to be collated and analysed; potentially, from local through district and regional to national and beyond.

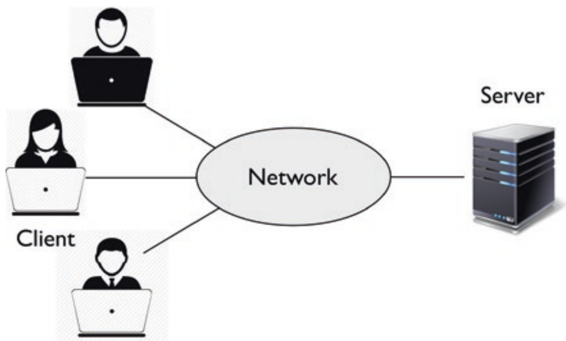
This hierarchy of interlinked components will rely upon several types of network topologies. There will be scope for close-proximity communication based upon an ad hoc network topology. This will support interaction from device to device in cases if these devices are at a similar level of data gathering and distribution (i.e. peer to peer). From sensor-based, passive items and mobile devices, data will be communicated to local networks and is likely to rely upon current technologies, such as WLAN and Bluetooth. In turn, LANs have connection through Internet Service Providers to wider area networks. Thereby, the different networking models will integrate and interact to provide an infrastructure at different levels of complexity.

A complementary perspective on these networking models considers the interactions between devices and systems in terms of communication. These models represent the mode of interaction between different devices in the networking context. A common interaction model is client–server (Fig. 11.2). This is the traditional form of Internet communication in which many smaller-scale systems interact via one or more larger-scale systems.

Another 'style' of communication between systems that has become common on the Internet is peer-to-peer interaction. This is characterised by systems or devices communicating directly with other similarly scaled systems (Fig. 11.3).

A less common approach to communication is also feasible. In this case, individual devices communicate with a central system that provides a repository of data and results. This allows each device both to deposit and to query the central

Fig. 11.2 Client–server communication model



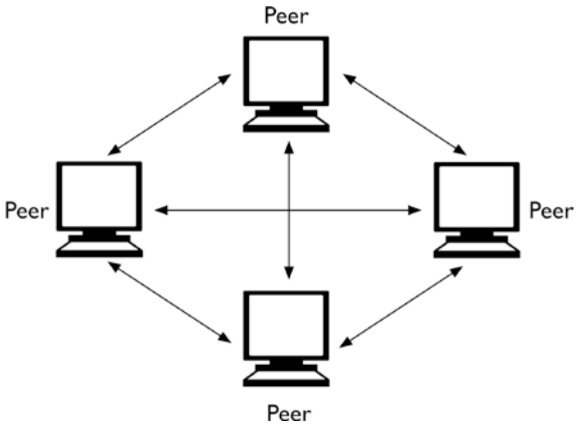


Fig. 11.3 Peer-to-peer communication model

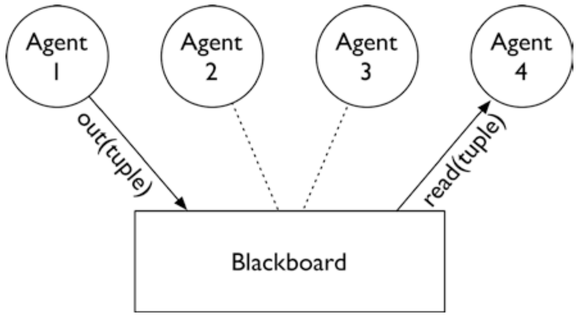


Fig. 11.4 Blackboard communication model

repository. This may be described as a '*blackboard*' model (Fig. 11.4) and shares many features of what has come to be called cloud computing.

The likelihood is that any significant installation associated with IoT would engage several of these communication models, while most individual components may employ a single model, most probably, the client–server or peer-to-peer approach.

With the increasing presence of communications infrastructure and interoperability of mobile devices comes new possibilities in tracking and monitoring of domestic objects outside the home—children, pets, vehicles, mobile phones and people. Of course, this is a double-edged sword that promises utility but also raises issues of civil liberty and personal privacy.

As part of a domestic or commercial IoT ecosystem, we have the promise of smart inventory, regulated service reports and associated ease of auditing and data production (e.g. for insurance purposes or home reports when selling property). Other features in prospect are highly integrated monitoring and control of heating, cooling and energy management at the domestic, district, regional and national level. Such environment monitoring for smart control may embrace ambient features and anticipated changes, e.g. weather forecast affecting thermostat settings.

With more devices becoming '*smart*' and able to register their status with upper-level systems, we should expect increases in device self-monitoring for fault tolerance and timely repair, e.g. as we have currently for vehicle engine status monitoring. Significant cost benefits may arise through better insight on system demand and better understanding of system performance. Allied to this may be quality of service enhancements through optimized device and system design as a result of greater performance feedback.

The costly realm of healthcare may expect to benefit substantially from remote diagnosis and treatment, as well as through operational enhancements. In the short-term, we may look forward to a more accessible, efficient and cheaper health service.

11.3 Issues and Challenges

Among the likely issues that are emerging or will emerge in consequence of wide-scale adoption of Internet of Things are the following:

1. Usability
2. Reliability and robustness
3. Availability
4. Locus of control
5. Privacy
6. Integrity
7. Security

11.3.1 Usability

Inevitably, with developments in ubiquitous technology there will be many difficulties that arise through inherent system complexity, or through system misuse. Some of the issues associated with Internet of Things are already evident in the nature and use of today's infrastructure. Other issues are predicted according to the manner and mechanisms that will sustain the growth in IoT.

From a user perspective, usability is always a major concern but key to progress in IoT is the trend toward '*invisible integration*'. As domestic and commercial items gain connectivity and native '*intelligence*', these facilities may become inherent and unseen, with little or no requirement for user activation or direction. In other words, the essential aspects of IoT may be invisible in their usual operation. If this is accomplished, and this may be more aspirational than realistic, then IoT technology will add little to any usability issues with connected devices.

11.3.2 Reliability and Robustness

Serious concerns associated with the reliability and robustness of devices and systems that constitute the Internet of Things are bound to arise. With greater dependence upon such integration comes greater risk. If complex integrated systems become mission or life critical, we will require assurance of reliability. This may require insight on minimum failure rates for critical devices and their higher-level systems.

With increased complexity we have multiple points of failure. The robustness and reliability factors affect individual devices, communication links, centralised and de-centralised services. Reliability is determined not only by failure rates or how robust are the constituent parts, but also in terms of capacity and associated levels of performance. Quality of service may be critical just as absence of device failure may be critical too. As with present day Internet connectivity, when demand increases, infrastructure capacity has a direct effect upon service performance. If there is a need to assign priorities and manage contention, then some services, and probably, some users, will lose out.

11.3.3 Availability

The issue of availability is closely allied to the concern for reliability and robustness. If system capacity is limited or not entirely reliable, how do we spread the benefits? Unless there is equal service provision (or at least, availability) for all, we risk a new era of 'haves' and 'have nots', in which the privileged (or the wealthy) have greater access, availability or performance than others. The prospect of emerging social benefits from IoT may herald a new realm of inequality of service availability determined by cost of provision or geographical location.

Perhaps we should expect differing service options at different costs. One case in point may be the rise of a two-tier national health service with two access modes: personal contact and online. Presumably, the latter will initially be the cheaper option but this might evolve into a more specialized service, e.g. advice and input from world leading medics, at a premium cost.

11.3.4 Locus of Control

Since IoT introduces major scope for data gathering and assimilation, the issue of control will concern many individuals and organizations. Current data gathering points, such as popular search engines, already raise questions of ownership, control and use of information. Similar questions arise regarding state access and use of information. If individuals yield control of information about their online and offline behaviour, they lose influence on how such information may be used. Optimistically, the information will be used positively to optimize services and minimize costs. Pessimistically, there may be adverse effects upon particular individuals or organizations, such as members of groups that are perceived as radical in their social, political or religious views.

In response, one might suppose that IoT leaves little scope for individual or local control of information. Indeed, one may argue that any 'added value' arising from the synthesis of data depends upon the aggregation of many data sources. Nevertheless, by its nature, the envisaged data aggregation requires authorised access to data that is ultimately derived from individuals or the systems and devices belonging to those individuals—and this naturally leads us to the issue of privacy.

11.3.5 Privacy

In this envisaged context of centralised data collection, we presuppose the application of data analytics across '*big data*'. As well as the aforementioned issue of control, we may ask '*Who owns the information*?' and '*Who determines how it may be used*?' Given that some people may wish to withhold information, can this be accommodated within the wider system? If not, can we secure guarantees that information in which we figure cannot be used in adverse effect against us? Along side the prospective benefits of timely intervention, e.g. based upon an individual's biological data, comes threats to privacy and civil liberty, e.g. through '*timely intervention*' and removal of health insurance benefits based upon an individual's biological data. Likewise, freedom of movement may be devalued if individuals are tracked via their use of mobile systems and have '*nowhere to hide*'.

On a less sinister note, collective data, e.g. associated with product performance and use, may hold great value to device manufacturer but afford little or no direct benefit to individual users. In the absence of incentive to contribute such data, will individuals have scope to opt out? More likely, participation will become a condition of system provision. If you want the service, you contribute the data.

Availability of data may raise questions over who will have access to such information. Increased resources of amalgamated data may generate new scope for data brokers and will certainly herald new avenues for personalized adverts.

11.3.6 Integrity

As we become increasingly dependent upon systems that relay information to higher-level systems, for data integration and analysis, questions may arise in our minds about the conclusions drawn from data that we have contributed. Assuming that the results are actually available for our inspection, can we trust the results of data analysis? Is there any scope for independent verification? At the domestic level, as well as relaying data to the supplier, smart metres may provide consumer feedback on energy usage. Access to the raw data and the basis for supplier cost calculations should allow us to determine the correctness of any resultant charges. But will all automated data transfer systems afford such transparency to the consumer? Alternatively, will intermediaries, such as industry watchdogs, have a role in policing the integrity and quality of such services?

11.3.7 Security

The security of systems and devices is our final area of concern with the Internet of Things. The preponderance of devices will only be as strong as its weakest point and we may expect many weak points in the explosion of interconnectivity arising from IoT. In anticipation of this issue, some have even dubbed the development '*the Internet of Insecure Things*', with the depressing thought that '*Anything that can be hacked will be hacked*'.

Evidence from existing networked systems and devices reinforces this unfortunate prospect. For instance, malware (allegedly originating in China) has been found on US SCADA (control) systems. Many nation states have growing anxiety over risks to national infrastructure, as evidenced by examples of attacks on the US power grid. A demonstration under Project Aurora, illustrated such vulnerability to attack, with a $1 million diesel-electric generator destroyed as culmination to the experiment. The frequency of data breaches is further indication that interconnections between systems may give rise to weaknesses as well as strengths.

One might suppose that developments in the form and function of newer devices would include protection against such risks. Yet the vulnerabilities persist primarily because the forms of attack are still effective. As previously noted, increasingly complex systems have more potential points of failure. Any party seeking mischief against an IoT installation may target individual devices or target the network and communication infrastructure. Most attacks use standard protocols to overwhelm the target. Since the connectivity and communication protocols are fundamental aspects of the system, they cannot be disabled as a defence. In consequence, any connected device will be vulnerable, by its nature. The inherent risks are unauthorized access (to data or control). With network access to a device, an intruder may retrieve stored data from the device or modify the device behaviour by means of remote commands or re-programming the device's standard behaviour.

Several prime examples of remote tampering have come to light recently. A case in point is the Internet-enabled fridges that use email to communicate their status [7]. In one instance, hackers have successfully gained access to the software system in such fridges and changed the programming to send spam emails. Similar remote access problems often affect Internet-enabled devices, including wireless-linked cameras.

Recent press stories report Web sites offering lists of remote cameras that can be viewed from anywhere on the Internet (without the permission, approval or knowledge of the camera owners). In one example, a Web site was found to be offering links to unsecured security cameras in 256 countries [8].

Remote access is often achieved by guessing a factory-set password that allows user control of the facility. Commonly, such devices are installed without change to their pre-set access passwords. Leaving them vulnerable to any remote user who can locate the device on the Internet and determine the required authentication details. The risk that unauthorised individuals may misdirect devices or acquire personal data from associated systems is significant and a realistic concern. In addition, experience shows that simpler remote interference with networked devices can impair or deny the service to legitimate authorised users or disable the normal operation of the device and its associated service.

Such interference is aptly termed '*denial of service*' and attacks of this nature often occur against Web services. In each instance, the attack is designed to fully engage the system and, usually, disable it through overloading its network inputs. Often, the technique will direct network traffic to the target service from many other devices that have been compromised, taken over and controlled remotely, without the knowledge of their owners. Such distributed denial of service attacks may simply overwhelm the limited capacity of the target to handle incoming communication or service requests. The assailed system may simply '*crash*' and cease to operate or fail to perform its normal operation while it is buffeted by the network onslaught. Such attacks may result in service disruption, data loss and associated damage to the public image of the affected organization.

The motivation behind such attacks may be mischief, political alignment or extortion against the owner of the target system. In the IoT context, the risk from denial of service attacks may range from inconvenience through financial loss and public image impairment to physical injury or death. Especially in a setting where we have implanted networked medical devices, the associated health risks from illicit access may be severe. This risk is recognised in the decision by former US Vice-President Dick Cheney, when undergoing heart surgery to have the wireless connectivity disabled on the implanted defibrillator [9].

11.4 The Future Internet of Things

The Internet of Things is not a utopian ambition. Technology exists that will enable many of the applications described in this chapter, and many more to be specified as the vision expands. In addition, the lauded potential social and economic benefits are plausible but not guaranteed.

As with many developments in technology, we may expect benefits and drawbacks. On the positive side, there are clear indications that the extensive integrated communication infrastructure that is fundamental to IoT will afford enhanced services through wider automation, information access and exchange. Those users who are able to quickly adapt and adopt the new technologies are most likely to benefit from these developments.

On the negative side, for a variety of social, financial or educational reasons, many prospective beneficiaries may be slow or ultimately unable to embrace the new opportunities that arise from IoT. Alongside the social and economic benefits, we may anticipate a new digital divide that arises from limited availability and incompatibility of old and new technologies. This gap may be amplified if some in society are unable to afford or to comprehend the technology and its potential, while others remain relatively unmoved and disinterested. Some may be content to adopt personal applications, such as health and fitness monitors or limited domestic management systems. The majority may rush to join the advance. The significant prospective impact of the Internet of Things lies in its broader application for social change and economic transformation. Achieving this potential depends not solely upon developments in technology but upon equitable access and affordable opportunity.

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Chapter 12
Home Technologies, Smart Systems and eHealth

Jorge Azorin-Lopez, Andres Fuster-Guillo, Marcelo Saval-Calvo and David Bradley

12.1 Introduction

The concept of a Smart Home, Digital Home or Domotics is based around the deployment a range of technologies to provide features and functions related to the management of the domestic environment [1]. Key components of such systems are:

Sensors	Provide information on the environment and its users
Actuators	Provide and perform actions based on the interpretation of the sensor data
Controller	Analyses and interprets the sensor data in order to generate the appropriate actions in response
Smart devices	Individual devices integrated within the network providing a range of smart functions
Internal communications	Integrates devices within the home network and provides link to external communications as required
User interface	Enables the user to interact with the system to define operating parameters and set context as appropriate

Referring to Fig. 12.1, the general functionality of the home system can then be considered in relation to:

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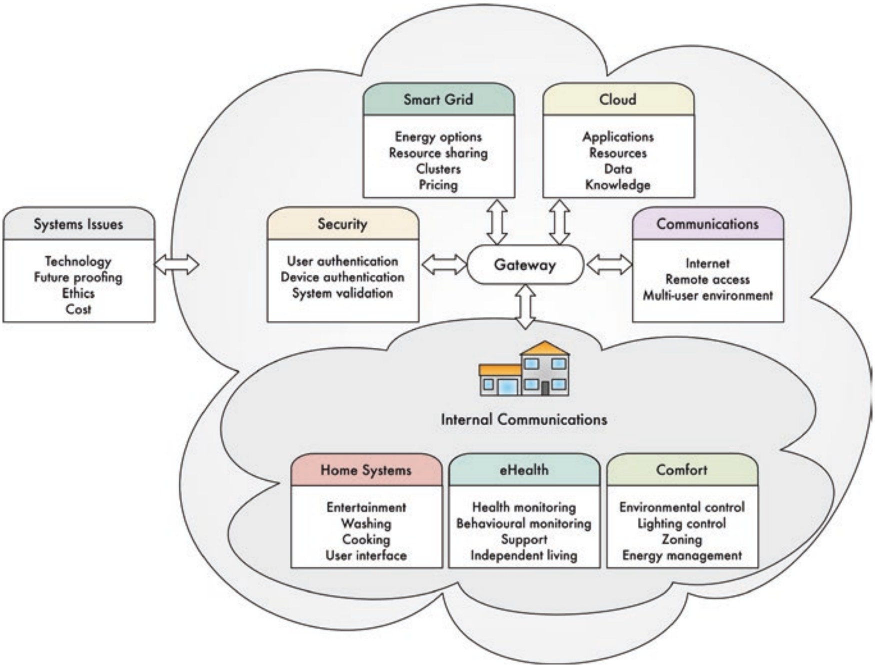

Fig. 12.1 Functionality of a smart or digital home

Cloud	Interaction with Cloud-based systems to provide a range of facilities and services
Comfort	This implies the operation of the environmental control systems to provide optimum comfort range for individuals within the home, including zoning to meet variations in individual user criteria and remote access as required
External communications	Supports the ability of individual systems within the home environment to access relevant, and context-based, information relative to their operation
eHealth and mHealth	Of increasing significance in the face of an ageing population and implies the introduction of a range of monitoring and response systems tailored to individual need
Home systems	Smart homes will inevitable and increasingly contain a range of smart, networked systems covering activities from entertainment to domestic functions such as washing, cleaning and cooking
Security	Implies both physical and cyber security under the general management of the home systems
Smart grid	Integrates individual homes within a group of homes and hence with the energy supply grids to provide efficient energy management and resource utilisation

The implementation of smart home and related technologies involves a number of systems issues for the short, medium and long terms such as the choice and future proofing of technologies, ethics and costs. The chapter begins by looking at the background to, and structure of, smart home technologies and systems before progressing to look at one particular area of application, that of eHealth and mHealth, in more detail.

12.2 From Domotics to Ambient Intelligence

Building automation services were initially provided by a set of non-integrated subsystems (heating, light control, fire alarm systems, escalators, etc.) within large buildings [2–5]. By the late twentieth century, this was starting to include home automation.

The introduction of the Internet then supported new concepts such as the *Digital Home*, *eHome* or *iHome* [6–8] and saw the evolution of the traditional automation services to include entertainment and communication supported by home networks and residential gateways [9, 10].

The twenty-first century also brought new paradigms such as "*ubiquitous computing*" [11] and "*ambient intelligence*" [12, 13], whose intent is to bring "*intelligence*" to the environment. In the case of ambient intelligence, this defines a context in which people will be surrounded by intelligent and intuitive interfaces embedded in everyday objects in an environment which will recognise and respond to their presence in a way which is sensitive and context dependent and which autonomously and intelligently adapts and responds to their needs [14]. As well as houses, this consideration encompasses spaces such as "*Smart Cities*" [15–17], strengthening concepts such as the Internet of Things (IoT) as is illustrated by the development of the associated terminology shown in Fig. 12.2.

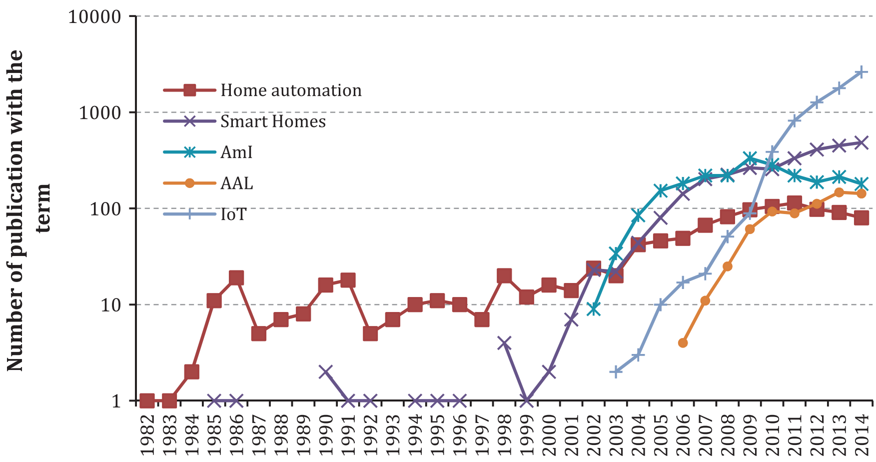

Fig. 12.2 Graphical representation of the evolution of terminology

12.2.1 New Services at Home

We are continually evolving our way of life, of work, of personal relationships and so on. For example, it is now common to communicate (i.e. talk, share information and so forth) almost every day with a wide community of individuals, some of whom we may never have met. From a technological point of view, more and more people seek an environment in which access to digital services from anywhere and at anytime is crucial. In this context, Information and Communications Technologies (ICTs) need to be continuously upgraded to adapt to the individual from two perspectives; services and technological infrastructure. For the former, people demand new electronic services to service their need while the technological infrastructure must support those services.

Traditionally, building automation and home automation have been associated with safety, energy saving and comfort through the automation of services such as lighting, environmental control and electrical appliances. In this context, it is common to distinguish "*personal security systems*", providing security services directly to a user, from "*central monitoring systems*" connected to remote sites. The progressive introduction of broadband to homes from the late 1990s then produced a change in the philosophy of service provision through the concept of the *Digital Home*, *eHome* or *iHome*.

In recent years, the Ambient Intelligence paradigm has supported the development of new smart devices integrated throughout networks to provide a service, for instance to distribute and display multimedia. Moreover, the trend of adding intelligence into devices is moving to wider environments as exemplified by the Internet of Things and Smart Cities. The resulting *Web of Everything* will integrate Smart Cyber-Physical Systems with the IoT to provide new forms of integrated service [18, 19].

12.2.2 Designing the Smart Home

Consider the following scenario. A user in the study uses a PC on a Virtual Personal Network, another user is in the living room, downloading and listening in real time to music on the home stereo, yet another user is reading online newspapers on a tablet and in the kitchen someone is doing the weekly shopping using the electronic whiteboard on the refrigerator.

In this scenario, several electronic services are being used. However, the technology remains visible to the users and people have to learn to use the individual technologies in order to access the required services. The longer the learning curve, the more visible the technology to the user and the more hidden the service. Further, communication and control networks are often unconnected and use proprietary systems.

Thus, in a current smart home the services and technology that provide support can lack integration due to their spontaneous emergence in response to a perceived need. As a consequence, services have tended to be specialised and the associated technology is quite visible. However, the trend towards more intelligent systems and components should enable environments to adapt to the user while hiding the complexity of the underlying technology.

The resulting solutions have to consider two key perspectives, integration and use. The former supports the provision of services irrespective of the technology used and allows for the interconnection of a wide range of devices. The latter, the user perspective, aims to support intelligent and transparent interaction by the user with the technology.

12.2.2.1 Integration of Services and Technology

Systems integration is an important consideration for the future of home technologies. ICTs develop from a continually evolving technological base and it is important that individual devices and systems are able to communicate with each other to provide more complex services involving both co-operation and competition for resources. In future, a distributed intelligence is likely to emerge from this interaction to support both system configuration and operation.

In this context, it is possible to distinguish three different networks within a smart home environment; namely control, multimedia and data, according to the functions managed by the network:

- The control network provides the infrastructure for those services identified with system automation and the management of simple commands and the regulation of specific levels. Requirements include low cost, ease of installation and reconfiguration, ease of expansion and fault tolerance. Devices connected to this network are primarily sensors, actuators and controllers.
- The multimedia network provides support for the distribution of audio and video. Requirements are related to the volume of data and the quality of service provision associated with the distributed audio and video data. Devices connected to this network are televisions, HiFi equipment and other media-based items.
- Data networks were initially associated with the sharing of computing resources such as files, programs and printers. With increased access to the Internet, the data network must provide access to it from anywhere within the home environment. Requirements include high bandwidth and low cost. Connected devices still include computers, printers, drives and scanners but also a wide range of other data sharing devices such as tablets and smartphones as well as increasing numbers of smart appliances.

The technology for each of these network types was initially proprietary or designed specifically to provide the services associated with them. Today, borders

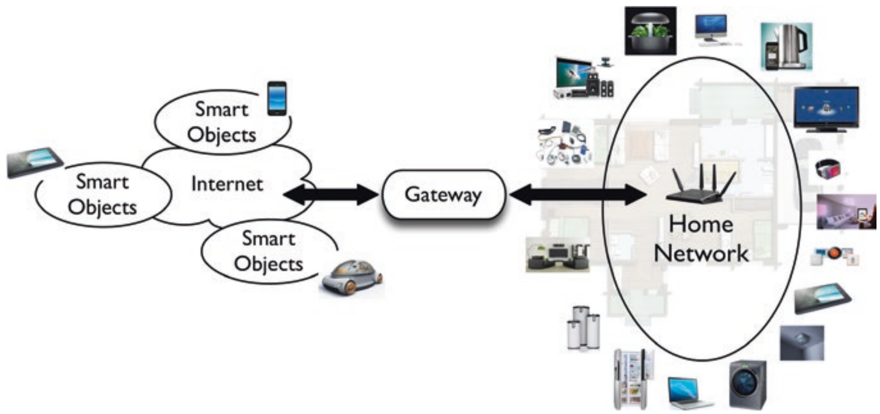

Fig. 12.3 Residential gateway

between multimedia and data networks are increasingly unclear as the bandwidth evolution of the data network[1] has resulted in the multimedia network becoming effectively a subset of the data network.

From the perspective of the control network, the majority of current technologies remain those designed specifically to provide home automation. However, convergence with data network technologies is increasing and control networks now contain devices able to connect to both networks. Hence, the trend is for a general convergence onto data network technologies.

Additionally, devices increasingly share information about themselves. For instance, lamps can provide a range of information including their status, energy consumption, hours of use and light levels, making them into a smart device. Other appliances such as refrigerators can become a smart devices notifying us (for example by email or SMS messaging) of shopping requirements, or even placing the order online themselves. The trend is thus towards intelligent devices which make use of network technologies to autonomously create larger, and more complex, integrated systems.

The result is a complex scenario of integration structured around services which are often specialised and strongly coupled to the technology that supports them. Moreover, services usually operate in isolation unless they have been explicitly designed to cooperate. The gateway as a concept then plays an important role in supporting communications between services and technologies through the concept of the *residential gateway* of Fig. 12.3 to provide a single, flexible and intelligent interface between external and internal networks.

Service and network levels were initially integrated with themselves and with each other in a centralised structure with the emergence of the gateway. However, the evolution of technology changes this centralised structure to a distributed structure

[1]Mainly technology structured around the IEEE 802 standard.

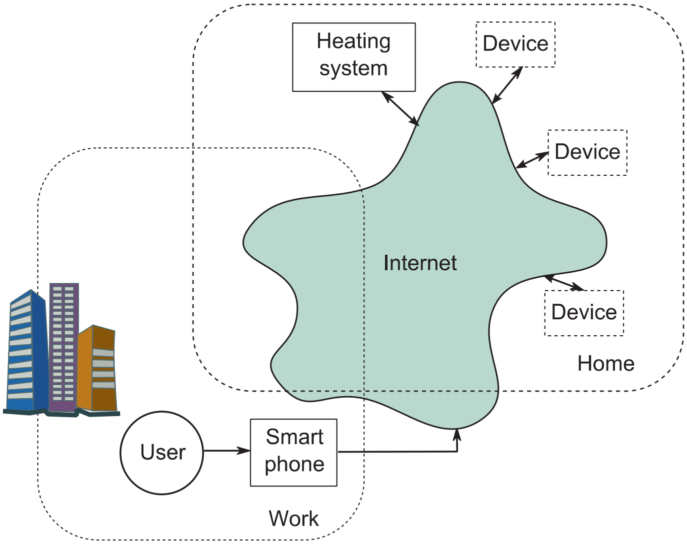

Fig. 12.4 A distributed system structure

in which the gateway supports any device with the necessary *intelligence* to enable it to interact with others [20, 21]. In the same way, individual services should have the ability to interact to provide a more elaborate service as suggested by Fig. 12.4.

There is therefore a technological challenge within ICT and the relationship with the IoT to provide a standardised architecture to support the development of new services. Horizon 2020 [22] commented that:

> The biggest challenge will be to overcome the fragmentation of vertically oriented closed systems, architectures and application areas and move towards open systems and platforms that support multiple applications. The challenge for Europe is to capture the benefits from developing consumer-oriented platforms that require a strong cooperation between the telecom, hardware, software and service industries, to create and master innovative Internet Ecosystems.

The above also implies the integration of smart components into cyber-physical systems. Here, Horizon 2020 commented that:

> Cyber-Physical Systems (CPS) refer to next generation embedded ICT systems that are interconnected and collaborating including through the Internet of things, and providing citizens and businesses with a wide range of innovative applications and services. These are the ICT systems increasingly embedded in all types of artefacts making “smarter”, more intelligent, more energy-efficient and more comfortable our transport systems, cars, factories, hospitals, offices, homes, cities and personal devices.

Related to this new generation of components and systems, the challenge of technological integration is to:

> …. develop the next generations of smart systems technologies and solutions, based on systemic miniaturisation and integration, of heterogeneous technologies ….

This is associated with the evolution of the *Future Internet* [23] focusing on a redesign of the original client–server architecture to resolve issues of security, trust and mobility. This future implementation has to meet:

> the ever larger portfolio of business models, processes, applications/devices that have to be supported, coupled with a rapidly growing number of application and societal requirements.

12.2.2.2 Serving the Service

The user has to perceive the benefits of the service but not necessarily the technology that support it. Although the integration of services and devices is an important consideration, designing the user interface is potentially more challenging. Interfaces have to be friendly and easy to use regardless of age and technology skills. For example, a person has to interact with a home system to use the service, define preferences, adapt services and so on. In this situation the concept of Maes [24] that:

> Autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed.

remains important for user interfaces.

The user interface has to emphasise autonomy while learning to perform tasks for their users and providing proactive assistance as necessary. The user interface could observe and monitor the actions performed by the user in order to learn, suggest or perform an action. Additionally, the user interface should have the ability to adapt to the user.

Consider a person who wishes to set the house temperature to be 20 °C when they arrive home from work. The most conventional solution is to programme the time at which the heating system turns on, with obvious issues for early or late return. A more evolved scenario would be the interaction of the user with the heating system via a website or mobile app. Taking this concept a stage further, the heating system could independently communicate directly with (say) the user's car or relevant public transport system and autonomously turn on the heating based on an estimated time of arrival, taking into account factors such as traffic, external temperature and the (learned) heat transfer properties of the building.

The final solution requires a distributed intelligence within the system enabling devices to cooperate or compete for resources and services. This implies smarter devices incorporating predictive, reactive and cognitive capabilities.

Another important issue is the volume of information that home systems are increasingly required to manage. Here, the predictive analysis of human behaviour is an important issue to consider as is the predictive analysis of the home as entity composed of different devices communicating with others both inside and external to the home. According to the CONNECT forum [25]:

> …. the integration of 'Things' as actors in the Internet via massive and innovative sensors, actuators, and real-time reactivity will cause another order-of-magnitude data explosion with challenges that we have yet to understand and deal with.

12.2.3 Home Systems Challenges

The most important goal is that of enabling individually intelligent devices to effectively communicate and interact with the other devices and actors in the environment. To provide intelligence at the device level, this could be seen as part of the service layer of the device where the decisions are taken regarding the service it provides. Alternatively, it could be seen as a layer which involves both services and technology as it both provide services and uses the technology in different ways depending on the requirements of the other devices in the environment.

At the technological level, advances are in two main directions, miniaturisation and performance improvement. Within the IoT, reducing the size of the devices to integrate them in essentially everything is an essential requirement, including implantable devices as part of an eHealth and mHealth environment.

12.3 eHealth and mHealth

In the introduction to the report '*Good health adds life to years: Global brief for World Health Day 2012*' Dr. Margaret Chan, the then Director-General of the World Health Organization,[2] wrote that [26]:

> Population ageing is a global phenomenon that is both inevitable and predictable. It will change society at many levels and in complex ways, creating both challenges and opportunities ….. This great demographic challenge of the first half of the 21st century therefore demands a public health response….

In another context, the World Economic Forum in their series of *Global Risks Reports* [27] has consistently identified mismanagement of population ageing as a high likelihood, high impact area lying on the societal axis of their analysis. This challenge of an ageing society is not only a global issue, as illustrated by Fig. 12.5a, b, but also one that is accelerating [28].

Globally, the effective delivery of all aspects of healthcare is an increasing priority, and the World Health Organisation commented that [29]:

> …. as long as the acute care model dominates health care systems, health care expenditures will continue to escalate, but improvements in populations' health status will not.

[2] Appointed 2007 and re-appointed for a further 5-year term in 2012.

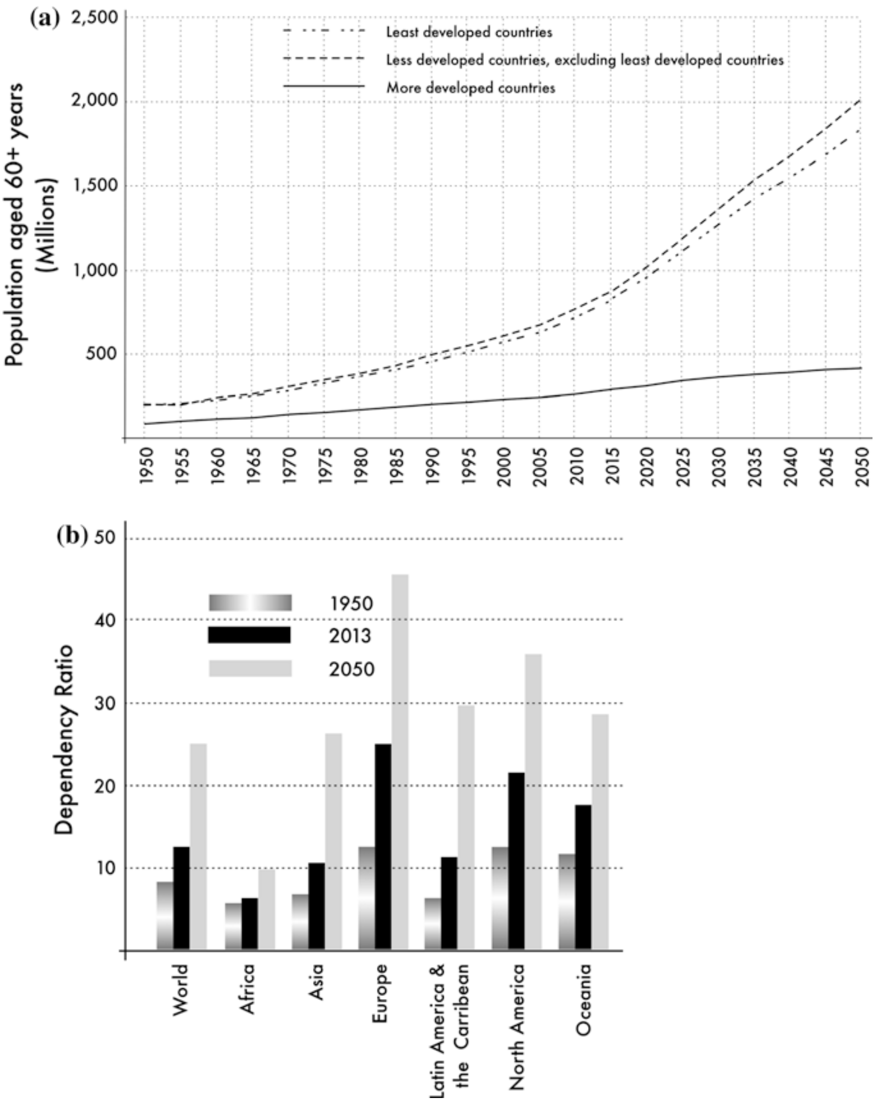

Fig. 12.5 The challenge of ageing. **a** Growth in population aged 60+ years. **b** Dependency ratios—defined as the number of people aged over 65 for every 100 people in the age range 15–64

Further, the EU Commission in 2009 noted that [30]:

> In order to limit the expected increase in public expenditure, policy measures which can either reduce disability, limit the need for formal care amongst elderly citizens with disabilities, favour formal care provision at home rather than in institutions or, more generally, improve the cost-effectiveness of long-term care provision, e.g. through introduction of eHealth and telecare must be developed.

These factors, together with the associated demands on physical, human and social resources, has led to a consideration of wide-ranging eHealth strategies deploying advanced ICTs as a means of providing the desired and required levels of support. However, the evidence base remains relatively weak and Demiris and Hensel in their 2008 systematic review of health related smart home applications [31] stated that:

> …. in spite of the growing number of initiatives in this area, the field is in relatively early stages and is currently lacking an extensive body of evidence.

and there has been little since to suggest a significant change in this position.

In practice, evaluation has to date tended to be based on relatively limited evidence, often structured around the extrapolation of relatively small data sets, which themselves are often concentrated around a focussed application or a selected group of participants. It is therefore suggested that such evaluation as does exist can perhaps best be categorised as trials aimed at establishing the performance of specific system components rather than establishing their functional and operational integration at the system level, for whom and in what circumstances [32, 33]. The effect has thus been that to date installations have essentially been experiments, and need to be considered and evaluated as such.

In the absence of a wider integration of such data as is available, access to which may well have commercial implications, this position of sparse data and lack of confirmation is likely to be the case for the immediate future.

There is also the concern that within the overall context of eHealth there has been an inevitable, and to a degree understandable, compartmentalisation of technologies and applications in order to integrate them within conventional healthcare structures and organisations. Thus for instance, physiological monitoring is often seen as a constituent component of telehealth, but not of telecare, whereas from both a technical perspective, and perhaps more importantly a user perspective, they form part of a continuum of applicable technologies.

It is also the case that there has been a significant shift in the nature of technology since telecare, telehealth and telemedicine systems began development in the late 1980s and early 1990s. Of these, perhaps the most significant has been the evolution of smart objects and their interconnection through the medium of the IoT. This level of connectivity is illustrated by Fig. 12.6 which shows the rise in the number of connected devices per person.

The result is a combination of technology push in the development of new and novel forms of sensing, cloud computing, near field communications, smart communications, adaptive and emotive computing, machine ethics, and user pull driving demands for increased service provision.

Developments such as the IoT and Cyber-Physical Systems imply the large-scale interconnection of a range of smart, and essentially mechatronic, objects to service information [34, 35]. This, however, represents a paradigm shift in systems development from an environment in which information is used to service artefacts to one in which (smart) artefacts are used to service information. This in

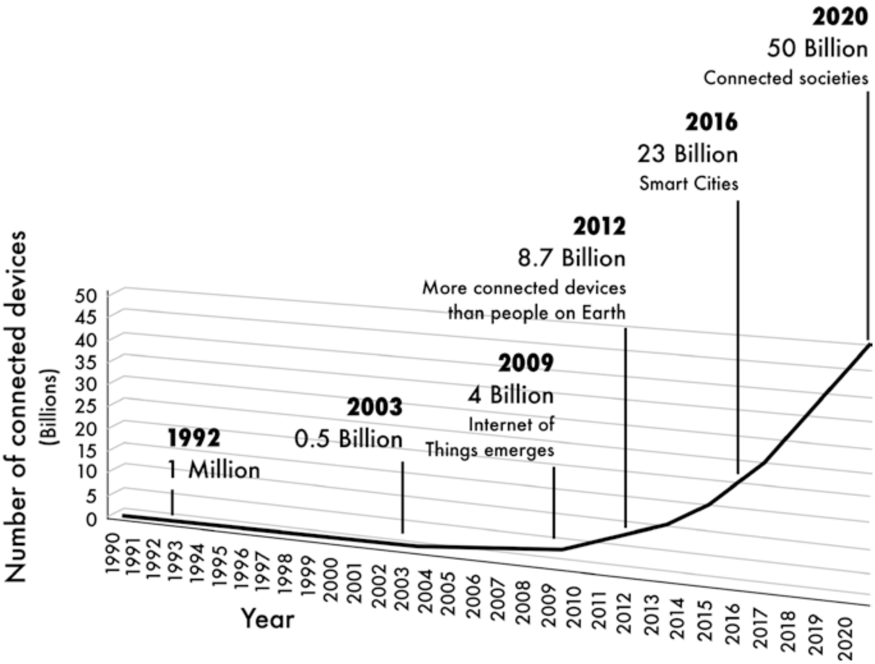

Fig. 12.6 Growth in connectivity

turn implies a change in the way in which systems are viewed as being relatively inflexible and task oriented to highly flexible goal-oriented entities whose role can easily be changed by reconfiguring the connected smart objects. In such an environment, connectivity, and the ability to configure user interfaces to suit individual requirement and need becomes paramount to system functionality.

Consider an eHealth system structured around the following core functions:

- The monitoring and analysis of activity to detect and respond to anomalies or indicators of changed status, and hence a change in need.
- Physiological sensing and the recording of symptoms.
- The monitoring of emotion and its integration with other forms of behavioural data.
- The recording of specific observational data related to the monitored individual.
- The use of smart interfaces to provide the link between the individual and the system.
- The use of the Cloud as a data storage and transfer medium.

In the context of the IoT this functionality can then be associated with appropriate groups or clusters of smart objects to provide the connectivity.

Table 12.1 Characteristics of technological and other forms of lock-in

Characteristic
• Consumption of resources continues to increase even after changes which would seem to permit reductions
• The take-up of a new technology is a function of the 'inertia', as expressed for instance through market position, of the existing technologies and systems
• Technologies become embedded within political, social and economic systems such as markets, patterns of consumer demand, systems of regulation and infrastructure
• Institutional lock-in arising from existing interests and an adherence to convention
• Inferior designs become fixed in use by a process in which circumstance are often as important as the design itself
• Established technologies often show economies of scale, and replacement with new designs and processes can incur significant structural and resource costs at the introductory stage, even where the long term consumption of resources, functionality, environmental impact and costs are likely to be superior

12.3.1 System Design Issues in eHealth and mHealth

A substantial background of research has defined the current state of knowledge and provided an understanding of the issues involved. However, there has perhaps been a trend towards increasingly complex technological solutions [36], potentially resulting in a lack of focus on the user. Approaches which compartmentalise system elements are inevitably vulnerable to a form of 'lock-in', in which self-reinforcing barriers act to inhibit change or prevent the uptake of new technologies or the integration of such technologies within established systems [37]. The characteristics of such a lock-in are summarised in Table 12.1, and are often associated with the levels of research, time and investment that have gone into a system or technology, and the resulting, and entirely understandable, desire to make this work.

To take advantage of developments in technology, it is therefore argued that there needs to be a more open approach to system design and implementation along the lines of the *Open Innovation* strategy as outlined by Chesbrough [38].

12.3.1.1 Sensors

The increasing availability of new generations of initially wearable, but almost certainly ultimately implantable, sensors capable of providing information on a range of physiological signs such as pulse, respiration, body temperature and movement needs to be accommodated within the next generation of eHealth systems. While the data from these, as for instance relating to movement, could be correlated with activity data derived from PIRs, they could also act independently in establishing, on a clinical basis, the requirements for an emergency response.

Specifically, the introduction of wearable, and eventually implantable, sensors supports a separation of the functions of monitoring and emergency response in a way which is linked directly to the individual. It is therefore argued that this form of sensing has the potential to play a significant role within eHealth and mHealth in a number of different roles, including [39]:

- The direct monitoring of a range of physiological parameters.
- The separation of functions such as general behavioural monitoring and emergency response with physiological data being used to supplement data from the behaviour monitoring system.
- The ability to extend the support for an individual from the home environment to the wider environment through the linking of the body hub or implanted sensors to mobile communications networks which would provide a continuous monitoring of the appropriate data.

12.3.1.2 mHealth

The coming together of the technologies of worn or implantable sensors with mobile communications affords an opportunity to expand the coverage to the environment as a whole, enhancing the ability of an individual to move between the home and the wider environment. Thus, an individual with implanted physiological sensors has an application loaded onto a smart phone to enable it to serve as their personal information node. This then allows their data to be monitored in both the home and wider environments.

In normal use, this data will be integrated with home derived data such as the recording of the use of space as part of the general monitoring process. Should an abnormal condition arise then depending on the nature of the abnormality, a number of actions could result, including:

- Messages passed to the care team for appropriate follow-up.
- The user advised of any immediate actions to take.
- An emergency response initiated if appropriate.

Should this condition be such as to cause, say, the individual concerned to be unconscious when the emergency response team arrive, the fact that they are linked to their health record would enable the response team, with proper safeguards in place, to access information such as known medical conditions and medication to enable a more effective response than might otherwise be the case.

Mobile health or mHealth-related applications structured around the use of mobile communications as a specific element within eHealth thus offer great promise. Applications include the collection of data, dissemination of information, and patients, real-time monitoring and related issues [40, 41].

12.3.1.3 Standards

Standards and protocols are competing for the home networking market are largely based around the IEEE 802.11 standard and its range of amendments. Their use for telecare applications is then dependent on systems providers adopting appropriate standards to allow for the networking of a range of devices. However, and for understandable commercial reasons, systems suppliers are at times reluctant to adopt an open systems approach, which would allow devices from a range of suppliers and providers to be integrated onto a single home network and which put in place appropriate safeguards for the handling of the health-related data generated [42].

In relation to eHealth systems, the ISO/IEEE 11073 Personal Health Data (PHD) standards [43] aim to support:

- The provision of real-time plug-and-play interoperability for medical, healthcare and wellness devices.
- The facilitation of the efficient exchange of care device data, acquired at the point-of-care, in all care environments.

12.3.1.4 Informatics, Data Security, Ethics and a Knowledge Economy

The integration and management of healthcare-related data from all sources presents a major informatics challenge in ensuring the robust and secure control of an individual's data whilst allowing appropriate access to that data [44]. Indeed, resolving questions of data and information security is likely to be a major issue in developing personal health databases to achieve the necessary levels of user confidence while ensuring appropriate access.

Other issues of growing importance are the ability to use an integrated health informatics system, sometimes referred to as a '*Learning Health System*' [45], in which the ability to use the information residing in an integrated health informatics system, and particular patient data, can be used in support of the planning, organisation and management of a health system, for instance through the identification of trends and patterns to enable earlier interventions to take place.

Such systems envisage an infrastructure along the lines of that shown in Fig. 12.7 in which related information can move freely between the strategic groupings associated with the provision, development and management of healthcare while relating back to the individual. Again, however, there are significant issues of security and confidentiality. In particular, the ensuring of patient anonymity while enabling the relevant data to be accessed for strategic purposes. Studies of the potential of cloud computing in healthcare [46, 47] have served to highlight and identify problems associated with the maintenance of data security within a shared environment whilst also suggesting pointers to potential solutions.

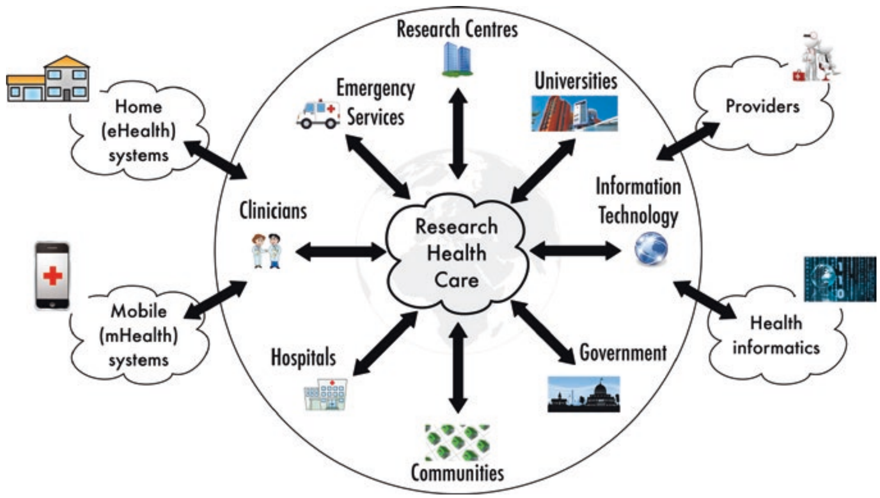

Fig. 12.7 eHealth/mHealth infrastructure

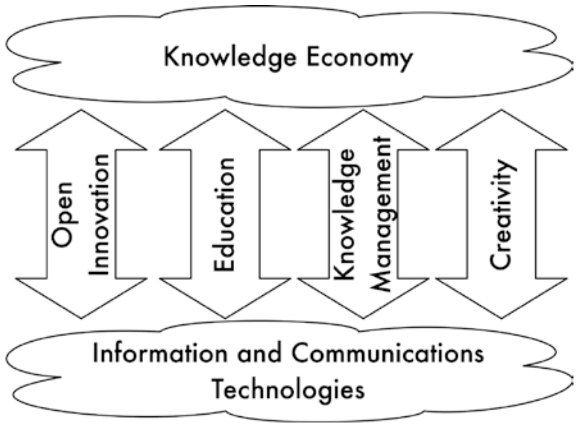

Fig. 12.8 Knowledge economy

Further, discussions regarding the general access to, and use of, anonymous data have confirmed the significant levels of concern associated with providing access to such data, even when it is recognised that the application is benign.

All of the above have ethical, both human- and machine-related, implications which will need to be addressed if the approach is to become adopted. In particular, there are the concerns of allocating the responsibility for the well-being of an individual to an autonomous computer based system which makes decisions on their behalf as to their state of health.

Further, such an infrastructure must be positioned within the context of an evolving knowledge economy as suggested by Fig. 12.8 within which the data and information relating to individuals may well be seen as having significant contextual, or indeed financial, value. Thus, concerns have been expressed that such data may be traded and used to prohibit access to certain levels of provision. The ethical issues associated with such information transactions, and their balancing to maximise the return to the individual while optimising the management of their healthcare provision will need to be resolved if eHealth and mHealth are to impact on such provision [48, 49].

12.3.2 eHealth and mHealth Challenges

In an environment seeing a rapid growth in the number of older people places significant additional demands on resources, including infrastructure resources such as housing, communications and transport. Further, many of these older individuals wish to live as independently as possible for as long as possible, posing societal challenges in ensuring access and mobility whilst preventing trends such as increasing urbanisation and the depopulation of rural areas, as for instance the Highlands and Islands' in the UK.

The underlying vision must therefore be one of an environment in which stakeholder needs are met through a sustainable organisation and the structuring of both the physical environment and the information environment to meet the changing needs of an ageing population.

Thus for instance, mobility must be considered not just as an ability to move within the physical environment, with all that that implies, but also mobility within the information environment, for instance through the deployment of new and novel approaches to interfaces and visualisation. It is argued that such enhanced mobility within the information environment then acts to support physical mobility, for instance through developments in mobile healthcare (mHealth) to allow aspects and elements of telecare to move with the individual rather than be fixed to their home environment.

This overarching vision of a healthcare infrastructure which integrates the physical and the information environments to support the user in turn implies the need for sustainable solutions which maximise benefits whilst optimising the use of resources in each of the short, medium and long terms. These solutions must address and support issues such as

- The balancing of the level of provision between urban and rural communities whilst recognising the needs of such communities.
- The nature of the housing stock and the balance between new build and refit or refurbishment.
- The ability to effectively assess need, specifically within the home environment rather than a laboratory.
- Means of capturing new and novel forms of data such as observational data.
- The design strategies to be adopted in relation to each and all of these issues.
- The nature of the tools to be used to support the effective assessment of the impact of change.

It must also be recognised that many current systems have over time been the subject of evaluation, review and indeed change. This has in turn often resulted in an interest, and indeed in some cases an investment in maintaining the status quo, resulting in a potential for a degree of technological lock-in which acts to inhibit the introduction of new concepts, methods and ideas. Meeting these and related challenges is fundamental to managing an ageing population.

Key issues for debate are therefore suggested as being:

- Establishment of user needs and requirements through interaction with the full range of stakeholder groups. This is an aspect of the process that is too often neglected and requires the development and implementation of conflict resolution strategies to ensure a balanced outcome.
- Identification of resources and of the interactions, both levels and forms, between different types of resource; i.e., human, financial, societal, infrastructure, etc.
- Infrastructure issues impacting upon both perceived and real issues of access and mobility.
- Sustainability issues impacting upon access to and availability of resources and including economic sustainability.
- Issues of user interaction and the incorporation of the necessary communications infrastructures within the built environment.
- Definition and evaluation of methods and techniques to carry out user evaluations in both the laboratory and the home environment.
- Design strategies and methods and the exporting of these to the relevant stakeholder groups.
- The development and implementation of decision support and related tools to inform decision-makers as to options and outcomes.
- The role of the IoT as a means of integrating a range of *smart* and *mechatronic* objects within that infrastructure.

The question must also be asked as to why, despite advances in technology that have taken place over the past 20 years, have there been no validated large-scale eHealth installations taking advantages of those technologies. It is suggested here that this is because the development of the systems required to make effective use of the technologies have lagged behind the development of the technologies. Requirements here are for:

- The deployment of the techniques of data mining and knowledge extraction as applied to large data sets and the dissemination of that knowledge to the individual.
- The restructuring of functional, organisational and operational systems and procedure within the overall context of healthcare provision to make effective use of new knowledge being generated.
- The future proofing, as far as is practical or possible, of such systems to take account of future developments.
- Ethical and security issues associated with the management of the growing volume of both generic and user-specific data.

12.4 Conclusions

A major focus of attention in the development of future Smart Homes is the ability to make the underlying technology as non-invasive as possible. Thus in relation to the user interface, computer vision and speech recognition offer many possibilities, but require improvements over current solutions. Included here is the need to achieve new and novel solutions that encompass machine intelligence to extract useful data from visual and audible information together with the communication protocols necessary to secure and fast communications. Developments up to the time of writing in these areas include Apple *Siri*,[3] Microsoft *Cortana*[4] for speech recognition and Microsoft *Kinect*,[5] *Leap Motion*[6] and *Sentry Eye Tracker*[7] for motion recognition based on computer vision.

While computer vision has the potential to simplify and improve the interaction of the users with a smart environment there still exist a number of challenges to be resolved, including:

- Facial expressions in adverse lighting conditions, for instance during the night when the light levels are low.
- The environment may host several people and the system may be required to extract both individual and global information, for instance to lead people to the safest exit in the event of fire.
- Provision of methods and means which ensure privacy, particularly where the system may be required to respond differently to the differing needs of different users.

Wearable devices also have the potential to support location independent services. These could include:

- Detecting and responding to dangerous situations such as a hole in the street or approaching traffic.
- Route guidance in unknown locations.
- Support in emergencies, for instance by informing users as to potential actions while autonomously communicating with emergency services.

In a wider system context, challenges include:

- The ability to analyse and respond to the level of activity in a street to autonomously regulate the lighting, traffic signals and other elements of the environment to optimise factors such as safety and energy consumption.

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[3] www.apple.com/ios/siri (accessed 8 October 2015).

[4] www.windowsphone.com/en-US/how-to/wp8/cortana/meet-cortana (accessed 8 October 2015).

[5] http://dev.windows.com/en-us/kinect (accessed 8 October 2015).

[6] www.leapmotion.com (accessed 8 October 2015).

[7] http://steelseries.com/gaming-controllers/sentry-gaming-eye-tracker (accessed 8 October 2015).

- Detect and report on damage to infrastructure to support pre-emptive maintenance.
- Detecting and responding to dangerous or hazardous situations and acting to mitigate these.
- The provision of design tools to support the design of integrated systems based around the presence of numbers of smart devices.
- Ensuring user privacy.

The chapter has set out to try, through the medium of the Smart House and eHealth technologies in particular, to suggest how the increasing availability of smart devices and systems will impact on the way in which individuals react to and interact with their environment, and to identify some key issues for which resolution is required in order that the user potential may be achieved.

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Chapter 13
The Changing Landscape of Enterprise ICT—Responding to New Possibilities and User Demands

Christopher Milne and Steve Watt

13.1 An ICT Practitioners Perspective

As Information and Communications Technology (ICT) practitioners and managers in a higher education institution, our work essentially requires the integration of a diverse range of elements to develop, implement, maintain and run a range of systems and services. These elements include people (internal and external); responses to legislation and regulation; organisational and user requirements; customers (internal and external); hardware; software; data; internal infrastructure and external (regional and national) infrastructure (e.g. the SuperJANET network). These elements are integrated at both systems and organisational levels, to provide what can be described as commoditised ICT systems and services. However, focus is steadily shifting from delivering commodity ICT systems and services to driving and sustaining organisational growth through business transformation by business process reengineering and structured around a range of enabling technologies, many of which incorporate their own integral software and systems. We therefore provide a different perspective on the opportunities and challenges that are likely to form part of the mechatronics futures, by reflecting on the key features of the changing environment that we operate in and the challenges of integrating the elements noted above to deliver services and secure business transformation.

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13.1.1 Developing and Delivering Services In-House Is Suboptimal

The environment and methods through which enterprise ICT systems are established to deliver services to end-users have changed and are continuing to change. Traditionally, the ICT function was predominately an in-house operation in terms of resourcing, approach and scope. Organisations invested to recruit, develop and retain a skills base necessary to deliver services provided by the in-house ICT function. The in-house work force would thus consist of core workers [1], that is permanently contracted employees, who (other than planned or unplanned leave) were readily available to the organisation, supplemented by non-core workers such as contractors, when specialist or unique skills were required on an ad hoc basis. Organisations sought ownership of their core in-house ICT infrastructure, with some equipment leasing taking place on the periphery. In-house services, as the phrase suggests, more often than not, were delivered within the geographical and physical boundaries of the organisation.

By their very nature, the majority of in-house functions are inward looking in so far as they are normally created to serve organisational requirements. Connectivity between in-house functions is the norm, with external networking being less prevalent and/or structured [2]. In a world where options for connectivity and collaboration in all forms are increasing exponentially; where resources are more scarce, or expensive and systems and services require a higher degree of integration—designing and providing systems and services with in-house working as the default philosophy is open to significant challenge. For instance, consider the collaboration across organisations to create the iPod and the associated changes in licensing necessary to allow end-users to access and download copyright material in different ways [3].

From an economic perspective, in many instances, designing and providing services based on in-house philosophies is now becoming a suboptimal approach to systems delivery and operation.

13.1.2 Cloud Computing

Advances in cloud computing are changing the enterprise ICT landscape, and in particular organisations are no longer bound by in-house provision. This is an exciting and welcome development, resulting in significant momentum in cloud adoption as a way of delivering services that once would be delivered by a combination of in-house development, hosting and support.

Expending resource to deliver services by establishing, implementing, maintaining, securing, developing and retaining, an ICT enterprise infrastructure that is part of an enterprise (in both physical and balance sheet perspectives) in a number of areas, no longer makes any business sense. Indeed, following this traditional service model can limit the capacity of an enterprise's ICT function to create value and competitive advantage. Cloud providers have developed the infrastructure economies of scale and new transformational business models. They can absorb new customers rapidly, providing services as modules, a form of enterprise plug and play.

In the higher education sector, student email services are a relevant example. Here, a significant number of UK universities now contract with cloud providers such as Microsoft or Google for those services [4], freeing in-house resource which can be used to deliver other services, or be returned to the business, adds greater value.

Cloud-based models of ICT service delivery require a new, and notably diverse, skills set—partner identification, contract and business relationship management, information governance, data architecture and developing back-out plans. How do you secure enterprise data from a cloud provider, returning this to the enterprise and/or a different infrastructure partner in the future?

This is changing the boundaries of systems analysis and design at the enterprise level, the Chief Technology Officer (CTO) or Chief Information Officer (CIO) focus is no longer on devices and device management. Infrastructure is the preserve of the cloud provider. Enterprise systems analysis and design now involves risk analysis, contract and data protection law and establishing a firm partnership. The risk analysis process includes due diligence around the cloud provider and an evaluation of all of the risks associated with both the intended current and future use cases and provider. This can include data sovereignty, location, security and exit options.

There is more value and scope to create competitive advantage by identifying a suitable partner and accessing third-party infrastructure available in the cloud. This creates scope to free in-house resource to create value for the enterprise elsewhere such as outsourced electronic mail, which is a relatively common example of Software as a Service (SaaS) and High Performance Computing becoming a more commonplace example of Infrastructure as a Service (IaaS). One can appreciate the value of this more by considering the outsourcing of mail scanning and filtering where a third-party supplier has access to a far larger database of threats than an on premise service, thus providing a better solution.

13.1.3 Focus Is Shifting from Device Management to Data Management

Our dependency on the Internet and on the many devices that connect to it continues to increase year on year. An "*always on*" society demands greater connectivity in a ubiquitous manner. Fuelling this further is the increase in common devices, such as digital cameras, televisions which now have Internet connectivity. Traditionally, such devices were used in isolation. Their purpose and functionality is now extending dramatically and a broader perspective on networking and data transmission is creating new opportunities and challenges along with increased demands from users and customers.

In less than a generation, the term "*online*" has moved from the lexicon of electronic engineering and computer science related disciplines to become embedded in almost every facet of daily life. Fewer activities now take place exclusively offline, or without an element of online interaction. People continually demand more from their online experiences—it is not good enough that a device works reliably and that connection to the Internet (or other networks) is seamless and near instantaneous. People are seeking higher levels of integration between devices and all pertinent data sources as for instance through citizen portals, student portals and online one-stop shops. Such services also need to be platform agnostic and responsive to cater for the range and variety of access methods and devices.

While devices and services are important, the value and the role of data should not be overlooked. Many organisations that were technology or device centric are changing their business models—selling data and/or data integration services is in some instances becoming more important than trading hardware.

In October 2011, Hewlett-Packard (HP) acquired Autonomy Corporation plc—a specialist in the analysis of unstructured "*big data*." While the financial prudence of the £7.4 billion takeover has been the subject of much comment [5], HP's purchase of Autonomy signalled a significant strategic shift towards revenue creation from processing of structured and unstructured data. That shift has continued. In November 2015, HP split into two separate companies: HP Enterprise will focus on supplying corporations with software, services, and hardware with HP Inc providing computers and printers. In 2014, the Microsoft CEO, Satya Nadella, in an email to all employees outlined the future direction of the company, signalling a shift in focus from devices and services towards mobile and cloud [data] [6].

13.1.4 Security

One of the greatest challenges which enterprises have recently come to face is that of cyber security. In the UK cyber security is considered as a Tier 1 threat, the same threat level as terrorism or natural disaster. With Gartner predicting that over 75 % of business will be "*digital*" by 2020 one can quickly identify the likely impact on both the enterprise and the end-user. It is therefore hardly a coincidence that the annual World Economic Forum Risk Report [7] has consistently identified cyber security and associated factors as a major and high impact risk area.

Large integrated systems like those which are found in most enterprises are complex systems of people, processes and technology [8]. They can also be considered as adaptive even as far as to say they can exhibit characteristics of having a life of their own. This has direct links back to the study of biological systems in that often their behaviour under certain circumstances is unpredictable. Should a security breach occur, it is very difficult to understand the implications on the many smaller systems which then integrate to form the enterprise system.

Enterprise local area networks (LANs) must now support a range of complex systems ranging from traditional network connected devices to embedded systems within intruder alarm systems, access control, building management systems, energy production, traffic control systems and many other instances. Each of these devices presents its own challenges especially where IP connectivity has been added by the manufacturer beyond the initial design phase. Recent work by Hyungjun [9] has highlighted key steps which must be taken to provide sound security in an IP-based SCADA environment. A well-documented example of such issues is in the area of SCADA where a number of security breaches have occurred as a result of poorly written or maintained software on such devices [10].

The nature of such systems often requires a non-traditional approach to security to be taken. It is also the case that the traditional approach to securing our networks is no longer acceptable—an issue that will only further be exacerbated as we move forward. Securing networks now requires focussing effort more on securing what is important to us rather than trying to implement a lockdown approach and trying to protect everything. Historically, a firewall between the LAN and the Internet provided an organisation with a level of protection from external threats by (theoretically) allowing only legitimate network traffic to pass through. This approach is no longer workable as so many devices located within the LAN require access to Internet resources. A focus on data security is now needed which recognises that the boundaries between the LAN and the Wide Area Network (WAN) are blurred. This is often referred to as the "*disappearing perimeter*" [11]. Every single endpoint now needs to be considered as a potential staging area for attack—with endpoints being a mixture of corporately owned assets, worker assets or visitor assets in the context of an enterprise. There will be an endpoint security resurgence as a result of the Internet of Things (IoT).

Focus should therefore be around securing the data rather than the organisation as it is data that is the ultimate target. As data can reside on physical servers, virtual servers or cloud-based services, the solutions required are different but must be managed from within the same management interface if a holistic approach is to be taken.

The impact of security on usability is another area which has also been identified as a barrier to adoption. A recent example in the education environment was the implementation of endpoint encryption. This was considered necessary to protect personal data and a policy agreed to implement a solution which would encrypt the data stored on portable ICT devices such as smart phones, laptops, tablets etc. The adoption of this solution was slow, and is still to this date seen as an impediment by users. Similar examples can be found where usability is often given more consideration than security, and indeed security is often omitted to ensure that the end-user experience is maintained—often resulting in disaster [11].

One of the many challenges within an open environment is identifying where legitimate user credentials are being used to carry out malicious acts.

13.1.5 Strategic Partnership Working

According to Prahalad and Krishnan [12], innovation is derived more successfully using a group of industry partners and customers rather than in the traditional way where one organisation would develop the full ecosystem themselves and involve the customer thereafter as a consumer of the end product and/or service. Bringing together the collective core competencies from a number of partners provides a better platform for innovation. There are some parallels to this to what we have outlined earlier in identifying that a future delivery model for IT Services will be better optimised if it is done through strategic partnering in a very open way. Prahalad and Krishnan refer to this as "*co-created value*". Parallels also exist with the work of Chesborough [13] around the concept of open innovation.

This approach is becoming more common and will inform organisational design as a new set of roles will be required to manage such relationships. This will include Relationship Managers and Contract Managers who specialise in contractual and supplier management rather than traditional management of infrastructure and in-house IT departments. This shift is also being seen when traditional enterprises move towards the use of commodity cloud services—whether public, private or hybrid resulting in a new skill set being required with strong engineering and integration skills.

Looking forward we will see a steady shift from CIO roles to CEO roles as Information Technology becomes a more integral part of corporate strategy. In summary, such roles will be focussed on solutions rather than the intricacies of service delivery.

13.2 Legislation, Consumer Protection, Privacy by Design and the IoT

Privacy legislation, current and anticipated, presents significant opportunities for the advancement of the Internet of Things where stakeholders, including information governance practitioners, come together in a new form of strategic partnership to proactively design products and services that have proportionate privacy considerations built in. This can be achieved by placing the "*Privacy by Design*" principle at the heart of product and service design [14–17]. Privacy by design requires that responses to data protection [protecting privacy] are embedded within the entire life cycle of a technology and/or service that utilises personal data in any form, from the start of the design phase, deployment, use recycling and/or disposal. Understanding and applying the philosophy and provisions of privacy legislation as an integral element of product and service design can provide a pathway for success as people are happier to engage with the IoT when they have more control over how their personal data will be used, and more certainty that the organisations who process their personal data are capable of protecting and maintaining privacy.

At the time of writing, the relevant legal framework that informs our thinking on service design and delivery to assess privacy issues arising from the use of personal data with the IoT is Directive 95/46/EC (*EU Privacy Directive*). Directive 2002/58/EC as amended by Directive 2009/136/EC (*EU Privacy and Electronic Communications Directive*). Article 5 of the latter requires that public communications providers such as Internet Service Providers and telecoms companies are required to take technical and organisational measures to:

> ensure the confidentiality of communications and the related traffic data by means of a public communications network and publicly available electronic communications services. [18]

Article 6 requires that providers of Web services that transfer messages from Web servers to Web browsers via text files (cookies) must inform users that these are being used, describe their use and secure consent before a cookie can be stored on a user's device. As those legislative provisions play a lesser role in privacy protection in comparison with the *EU Privacy Directive*, assessment of the legislative frameworks to protect privacy in the development and use of the IoT focuses on the *EU Privacy Directive*, and the forthcoming *Regulation of the European Parliament and of the Council on the protection of individuals with regard to the processing of personal data and on the free movement of such data* (*EU Data Protection Regulation*) [19].

Naturally, these provisions apply to EU Member States. However, their reach is not restricted to the geographical boundaries of the EU and IoT device manufacturers based outwith the EU may be surprised to learn that they will fall within the scope of the directive where their devices are used within the EU to process personal data. Thus, a US manufacturer who produces a pedometer, which transmits data relating to the device owner to their social media feed will, when the device is used within the territory of a EU member state, fall within the scope of the legislation.

The sphere of influence of EU Data Protection legislation on the future development and operation of the IoT will be substantial, as the EU Data Protection Regulation provides specific provision in Article 23 that:

> [Privacy by design] *give incentives to* [data] *controllers* [organisations that decide how an individuals' personal information are to be used] *to invest, from the start, in getting data protection right (such as data protection impact assessments, data protection by design and data protection by default). The proposals place clear responsibility and accountability on those processing personal data, throughout the information life cycle*. [20]

The effects of the above will be far reaching, as for the first time, legislation (supported by significant monetary penalties) will require that [legal] entities who collect and determine the purposes for which personal data will be used, must proactively respond to EU privacy legislation by adopting data protection by design.[1]

[1]Also referred to within the legislation as "*Privacy by Design*.".

13.2.1 Privacy by Design

Privacy by design first emerged as a term in 1995, from the joint work of Information and Privacy Commissioner of Ontario, Canada and the Dutch Data Protection Authority. That work was closely related to "*privacy enhancing technologies*" and the principles of "*data minimization*" [21]:

> explored a new approach to privacy protection, with a number of case studies to show that systems with no personal data—or at least with much less personal data—could have the same functionalities.

Work to develop the concept of privacy by design continued, culminating in 2009 with the publication of a statement of seven foundation principles [22]. The third principle "*Privacy* ***Embedded*** *into Design*" demonstrates how the concept is an approach of systems engineering, where privacy requirements are considered and addressed throughout the whole of the engineering process:

> Privacy is embedded into the design and architecture of IT systems and business practices. It is not bolted on as an add-on, after the fact. The result is that it becomes an essential component of the core functionality being delivered. Privacy is integral to the system, without diminishing functionality. [22]

While the EU Data Protection Regulation establishes a legislative requirement for organisations to respond to privacy considerations by adopting data protection by design and by default, responding to Regulation is not the only driver for change. The growing number of security breaches, where systems and data are compromised, requires a fundamental response, at the systems level:

> In fact, security breaches may well be a structural problem for an information society that is increasingly dependent on the good performance of ICT. This should therefore also be seen as an opportunity for 'Privacy by Design'. [21]

Given its scope and reach, EU Privacy legislation will be a dominant factor in the shaping and development of the IoT, not least should privacy by design become a persuasive, proactive response to privacy protection.

13.2.2 Consumer Trust, Data Sharing Sensitivities and Market Success

Data, notably personal data, is a critical asset, fundamental to driving technology innovation. The use of such data, to develop existing applications, services, products and business processes in addition to the creation of completely new ones, are recognised as a substantial source of economic growth. However, in parallel, consumers' concerns as to whether organisations can be trusted to make use of their personal data properly are growing [23]. These concerns are not limited to organisations which use personal data to drive product development. Many organisations also derive competitive advantage from [big] data mining and analysis that deliver insights that are used to drive business/organisational decisions sourced from user behaviour data. Consumers are increasingly concerned about how their personal data is used in this space [24].

Treacy and Breuning [25] in their assessment of the interfaces between the development of the IoT and the Data Protection Directive, conclude that for the IoT to reach its full potential, businesses need to take cognisance of consumer privacy concerns, putting in place effective strategies to produce products and services that consumers are happy to use, with their personal data.

> Organisations wishing to take their products and services to the next level [the IoT] will need to identify the privacy risks and work to mitigate these before embarking on such projects. [25]

The Article 29 Working Party is comprised of representatives from each EU Member State's Data Protection Authority,[2] the European Commission and the European Institutions and publishes opinions and recommendations on elements of European data privacy laws that it feels are significant [26]. The Working Party also holds the view that for the IoT to be [commercially] successful, that organisations must address consumer privacy concerns.

> Indeed, empowering individuals by keeping them informed, free and safe is the key to support trust and innovation, hence to success on these markets. The Working Party firmly believes that stakeholders meeting such expectations will hold an exceptionally strong competitive advantage over other players whose business models rely on keeping their customers unaware of the extent to which their data is processed and shared and on locking them into their ecosystems. [27]

Consumer and Regulator privacy concerns surrounding the development of the IoT are understandable, as without the ability to capture, record, transmit, analyse and further process individuals' personal data, development of the IoT would come to a halt.

13.2.3 Personal Data at the Heart of the IoT

The concept of the IoT has been stated as [28]:

> A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.

"*Things*" in the context of the IoT are commonly accepted as smart devices or objects designed to process data linked to other similar objects or people. That data typically captures or can be linked to usage activities, which is then often recorded and/or transmitted. Devices and data are also often associated with unique identifiers that allow for interaction with other devices/systems within a

[2]The Information Commissioner's Office in the case of the UK.

networked environment. It is thus inescapable that data is one of the fundamental constructs of the IoT, and given the interaction between “*things*” and individuals, much of the data are personal data. The Working Party is very clear on this point.

> IoT stakeholders aim at offering new applications and services through the collection and the further combination of this data about individuals – whether in order to measure the user’s environment specific data “only”, or to specifically observe and analyse his/her habits. In other words, the IoT usually implies the processing of data that relate to identified or identifiable natural persons, and therefore qualifies as personal data in the sense of Article 2 of the EU Data Protection Directive. [27]

13.2.4 How Can Stakeholders Come Together to Ensure Privacy Protection in the Entire Life Cycle of an IoT Artefact?

In September 2014, the Working Party issued an opinion on the IoT. This identified the main privacy risks, within the framework of the Data Protection Directive, and recommendations for addressing those risks.

> The recommendations offer a practical view of what IoT stakeholders should consider when developing and marketing their products in compliance with not only the current EU data protection framework, but also taking into account [successor legislation] the upcoming EU General Data Protection Regulation. [29]

Shortly after the working Party Opinion was published in January 2015, the United States Federal Trade Commission (FTC) published its staff report: *Internet of things—Privacy and security in a connected world* [30].

The publication of these papers is welcome. Accepting the relatively short period of time that has elapsed since their publication, it is understandable that many IoT stakeholders have not yet had the opportunity to consider the issues and recommendations put forward. A consensus has yet to emerge on how privacy rules may be applied in a way that strikes the right balance between encouraging and stimulating innovation of IoT ecosystems and protecting consumer privacy [31].

The Working Party and the FTC share much common ground in their assessment of the nature of the privacy risks emanating from the IoT, for consumers, many of whom may have no option other than to interact with that ecosystem. There is also common ground:

> that core privacy principles such as transparency consent and data minimisation should apply in an IoT ecosystem. [31]

A significant difference between the markets of the United States and European Union lies in the fact that federal data protection laws only exist in European Member States. Not only is the Data Protection Directive well established, this legislative framework will shortly be extended with a single Data Protection Regulation [19]. Thus, in terms of exploring frameworks within which IoT stakeholders can purposefully come together to ensure proportionate responses to consumer privacy concerns throughout the entire life cycle of an IoT device and consequent processing and transmission activities, the opinion of the Working Party therefore is a valuable foundation and reference point. As the IoT develops in parallel with privacy jurisprudence, more specific mature guidance on establishing privacy as a core component of product and service by design will emerge. It is fundamental that future thinking in this space emanates from a multidisciplinary focus—technologists and privacy/information governance practitioners need to come together, otherwise innovation will become stifled.

> The IoT will not just requite technological innovation. Legal innovation will be at a premium. New thinking and new paradigms are required if IoT stakeholders, many of whom are based in the US, are to have any hope of complying with perspective and evolving EU privacy laws [and increased customer demands for privacy]. One internet, one thing, two worlds. [32]

13.2.5 A Roadmap for Collaboration

In framing IoT privacy considerations, the Working Party started with a pragmatic baseline, working within the scope of real-world IoT facets which are currently commercially viable: *wearable computing*; *the quantified self* and *home automation* or *domotics* [27]. While the future direction of IoT developments is uncertain, as other possibilities for viable commercial applications have yet to emerge from the:

> convergence and synergies of the IoT, with other technological developments such as cloud computing predictive analytics [27].

The European Commission are committed to: "*implementing a single, technologically neutral and future-proof set of rules across the EU*" [32]. Given the jurisprudence of data protection laws in the UK and Europe since the Younger Committee on Privacy [33], the Council of Europe Convention 1981 [34] and the EU Commission proposal for reform of the Data Protection Directive are derived from and continue to be focused on principles that can be applied to all forms of electronic processing of data—the recommendations from the Working Party Opinion [27] are likely to remain relevant, capable of being applied to cover future IoT developments, as that ecosystem evolves.

13.2.6 The Extent to Which IoT Stakeholders Are Engaged by the Legislation: Roles and Responsibilities

To develop effective responses to IoT privacy concerns, an important step is to understand the roles and responsibilities that IoT stakeholders have in relation to the legislation. There are two primary actors, the data subject, who is a (living) person that is the subject/focus of the personal data and the data controller, who is a legal entity that determines either alone or in concert with another party (a joint data controller) the purposes for which personal data will be used. The legislation ***only*** applies to the data controller.

In 1999, the [then] chief executive officer of Sun Microsystems, Scott McNealy, stated to a group of reporters and industry analysts that consumer privacy issues are a "*red herring*" and that "*You have zero privacy anyway… Get over it.*" [35]. McNealy's statement failed to take into account, at least in the European context, the fact that where an IoT stakeholder qualifies as a data controller, they have significant responsibilities for protecting and maintaining the privacy of customer or data subjects' personal data. From a consumer and legislative perspective, data controllers cannot afford to bring to market devices and/or services that are not capable of maintaining customer privacy. Arguably therefore, privacy is a core functional design element of IoT things and services. Responsibility for protecting the privacy of the consumer starts and ends with the data controller.

The Working Group in establishing their view of the IoT identified six key stakeholders. Table 13.1 then sets out the relevant stakeholder roles.

Table 13.1 Stakeholder responsibilities

Stakeholder role	Notes
Device manufacturers	Defining the functionality of a device and creating the ability for it to operate means that a device manufacture will determine what data is captured and the subsequent modes of processing/operation, which can include onward transmission of data to another device or service provider. Determining the purpose of data processing qualifies a device manufacture as a data controller
Social platforms	Data subjects may share their personal data, captured via a range of devices via social media. Sharing of data collected and aggregated by IoT "*things*" on social networks typically happens automatically via default settings configured by the user. Personal data pushed to a social media platform will be processed by the service provider for distinct purposes, established by that provider. This will then qualify the provider as a data controller
Third-party application developers	App developers process personal data via APIs. Unless the data received/collected by the API for processing has first been anonymised, the app developer will have determined the purposes for data processing and will qualify as a data controller. The app provider must clearly inform the user as to how their personal data will be processed. Otherwise, informed consent will not have been provided and continued processing will be unlawful
Other third parties	A third party could take the form of an insurer, who provides pedometers to monitor exercise, with the aim of adjusting health insurance premiums accordingly. The third party, unlike the device manufacture has no control over what data is collected by the device. The insurer has determined that the physical activity of a person will be measured in order to offer lower insurance premiums. Determining that purpose of data processing qualifies the insurer as a data controller
IoT data platforms	Cloud providers that store data collected through IoT *things* will be data controllers, as they determine how data will be stored, secured, received and transmitted between devices, etc., thus qualifying that service provider as a data controller
Individuals as data subjects: subscribers, users, non-users	Users of IoT devices can qualify as data controllers where they collect and process the personal data of others, for non-domestic purposes. The use of smart glasses is likely to collect personal data about others

13.2.7 Legal Basis for Processing Personal Data as a Foundation for Product and/or Service Design

In responding to privacy as a core functional design element of IoT *things* and services, understanding the legal basis for processing personal data is fundamental. Before personal data can be used, IoT stakeholders who provide devices and/or services (where the provider qualifies as a data controller) must ensure that their devices/services are capable of fulfilling at least one of the six requirements of Article 7 of the EU Data Protection Directive. That said, in reality only three requirements are likely to be of concern to product designers and service deliverers. Critically, products and services must be designed and managed so that they are capable of successfully engaging those requirements.

This will by no means be an easy task: providing users with the functionality to have full control via consent on how their personal data is used and evidencing that consent was or was not provided (potentially continually opting in and out of services and device functions) may require that granularity at the heart of product and service design becomes a fundamental consideration. The three requirements of the six available from Article 7, that are more likely to apply as set out in Table 13.2.

Table 13.2 Requirements of EU data protection directive

Requirement	Notes
Consent	People need to be fully informed as to how their personal data will be used, and by whom; where a user opts to consent, that consent must be explicitly captured and that fact recorded; users also have the right to withdraw their consent—this will have to be managed as part of product and service design. Fundamentally, IoT systems design must provide for robust consent management—where users can continually opt in or out, without any disadvantage: they must retain the right to have full use of the functionality of the system/service that they have paid for [36]
Contract	Use of personal data by IoT devices and/or services can be legitimised where there is a contract between the data controller and the data subject. The use of personal data must be necessary to fulfil the contract, requiring "*a direct and objective link between the processing itself and the purposes of the contractual performance expected from the data subject*" [27]. For the contract to remain valid, there cannot be any creep in the use of personal data. The collection and use of personal data must be clearly understood and defined as part of device and/or service design
Legitimate interests	A data controller can process personal data, and share this with a third party where it is their legitimate interests or those of the third party as long as the fundamental rights of the data subject are not undermined. As the privacy concerns of data subjects are fundamental, it is unlikely that a data controller can successfully claim economic interests as a justification to legitimise their processing of personal data

13.2.8 Challenges: Protecting Privacy Within the Internet of Things

The Working Party in forming a view of the privacy challenges related to the IoT identified six areas of concern as set out in Table 13.3. The Working Party's views on how these challenges can be addressed, as design considerations for the IoT are set out in Tables 13.4 and 13.5.

13.2.9 IoT Privacy Design Requirements

The Working Party's recommendations provide guidance to IoT stakeholders on the design and service considerations that in their opinion require to be addressed to establish an IoT environment that is compliant with privacy

Table 13.3 Areas of concern

Privacy challenge	Impact
Lack of control and information asymmetry	Given the ubiquitous nature of the IoT, where a stakeholder processes personal data unknown to the user, people may find that they rapidly lose control of their privacy, where they then become subject to third-party monitoring, notably where their personal data is disseminated to other stakeholders without prior knowledge or consent
Quality of user's consent	It is relatively easy for IoT stakeholders to be invisible to users. If a user is unaware of the data processing that is taking place, then consent cannot be relied upon as a lawful basis for processing personal data. Data subjects must be informed that processing is taking place
Inferences derived from data and repurposing of original processing	With the increased volume of data generated by the IoT, combined with advances in data analysis and cross-matching, it becomes easier for secondary forms of personal data to be generated and used for purposes beyond those that were originally intended
Intrusively bringing out of behaviour patterns and profiling	In the IoT the proliferation of sensors/devices, makes it relatively easy to build up a picture of a person's life from trivial or even anonymous data. Data harvested from the IoT, could be used to predict future behaviours, leading to significant privacy intrusion, where a data controller makes a decision on an individual, based on future profiling
Limitations on the possibility to remain anonymous when using services	The nature of the IoT is likely to make it extremely difficult for users to use services anonymously, as the connection between a user and a device will more often than not be inextricable
Security risks: security versus efficiency	It may be difficult to implement many security measures on IoT devices such as sensors, where there is a trade-off between hardware-based encryption and battery life. Integration of physical and logical IoT components, provided by a range of stakeholders only provides a level of security at the weakest point in the chain. IoT devices that become everyday objects present a new distributed target

Table 13.4 Privacy design requirements for all IoT stakeholders

Requirement	Action
Privacy impact assessments ("PIAs")	PIAs undertaken prior to the launch of any IoT entity. PIA methodology recommended for RFID applications [37] should be considered
User empowerment	Data subjects rights must be recognised and respected—users must retain control over their data at all times Data subjects as consumers/users should not suffer any economic penalty or service degradation if they opt not to consent to the use of their personal data. Consent should be granular—focused on specific areas of processing. Data subjects should have the facility to continually withdraw their consent, without having to exit from the service provided [38] All IoT stakeholders must be able to communicate to ensure that user choices are respected and acted upon. IoT devices and services should operate with a do not disturb function—including the facility to disable and enable sensors
Data minimisation	Most IoT stakeholders only require aggregated data Stakeholders should delete raw data as soon as that data has been extracted for processing Deletion should take place at the closest point of data collection of the raw data
Privacy by design and privacy by default	Principles of privacy by design and privacy by default to be applied by all IoT stakeholders
Transparency	Information on the use of personal data by IoT stakeholders should be made available in as user-friendly a manner as possible. Such information should not be confined to general privacy statements that are available from terms and conditions

legislation. Recommendations that are common to all IoT stakeholders are set out in Table 13.4. An overview of the obligations that are specific to a stakeholder are provided in Table 13.5.

Thus, those who seek to take their products and/or services into the IoT ecosystem will need to understand the fundamental concepts of privacy legislation, and work to mitigate privacy concerns as a core element of product and/or service design. A clearer picture is beginning to emerge of the initial suite of design considerations that IoT stakeholders will have to address.

13.2.10 Starting Points for Multidisciplinary Working to Innovate Across Technology and Privacy Legislation

Considering the recommendations and their context (Tables 13.4 and 13.5) reinforces the earlier point that development of the IoT will require multidisciplinary working as a level of technical and legal innovation will be a prerequisite for success. Therefore, a fundamental consideration is how best can the relevant

Table 13.5 Privacy design requirements for specific IoT stakeholders

	OS and device manufacturers	Application developers	Social platforms	IoT device holders and additional recipients	Standardisation bodies and data platforms
Privacy impact assessments ("PIAs")		Special attention to types of data being processed—notably the possibility of inferring sensitive personal data			
Privacy by design and privacy by default	Dedicate components to provide encryption services	Minimise personal data collection—strictly to purposes of processing			Develop lightweight encryption and communication protocols
Control by the user	Provide users with tools to read, edit and modify data before this is made available to a data controller				Data formats clear and self-explanatory: users should be clear on what personal data is being collected and transferred
Transparency				Users of IoT devices should have the functionality to inform others that their personal data may be collected in the presence of a device	
Data Portability	Users should be enabled to transfer their data to other devices	Tools should be provided for users to export both raw and/or aggregated data in a standard and usable format	Default settings prompt users to review, edit and confirm before data from IoT device is published to social media		Promotion of portability and interoperability standards
Data minimisation	Minimise storage of personal data on device to that which is necessary Raw data transferred to aggregated data on the device Provide the facility to irreversibly delete/destroy personal data	Minimise the amount of personal data collected to that required to provide the service Users should be offered the facility to use services anonymously			Focus on the format for raw and aggregated data. Promotion of data formats that contain minimal numbers of strong personal identifiers to facilitate anonymization of IoT data

multidisciplinary elements come together in academic, professional, practitioner and organisational contexts to provide and sustain the required technical and legal innovation necessary to provide for an effective IoT ecosystem?

Understanding and recognising when data makes the transition from data to personal data or sensitive personal data will be critical in designing and providing effective privacy solutions for the IoT. In that regard, an area where technical and legal innovation can come together is the area of developing and integrating anonymization techniques [38] into the design process. The purpose of anonymization is to turn data into a form which does not identify individuals and where identification is not likely to take place. This will allow for a much wider use of the information, while mitigating privacy risks for the data subjects. Successfully anonymized data will also fall out of the scope of data protection legislation, which by extension will reduce pressures on IoT stakeholders where the scope of their responsibilities as a data controller can be reduced.

Working to embed Privacy by Design principles as a foundation of systems analysis and design will also be a significant step. This may also involve establishing new interfaces/partnerships (see earlier theme of the chapter), with designers, engineers, information governance and privacy practitioners coming together within the product design and requirements specification phases. For example, the requirement to advise users as to how their personal data is being processed, which will include how data is collected and transferred across the IoT, to other stakeholders who are data controllers, could be aided by repurposing business data flows/process maps to explain what processing takes place and when to users. This level of analysis can also be utilised, in an attempt to reduce the likelihood of incremental creep in the processing of personal data.

Mapping out the processing and understanding data flows, notably when data can take on new meaning, will assist in establishing processing boundaries. Having determined the process boundaries, these should then inform the design phase, with the view of developing products/services that guard against any drift into illegal uses of personal data, notably where inferences can be derived from data and repurposing beyond the lawful justification for processing. This may mean that data controllers can rely more heavily upon contract as a legitimising basis to process personal data, reducing the requirement to rely on consent—which could then simplify product and service design.

13.3 Conclusions

To respond successfully to the changing landscape, creating the capacity to secure new possibilities notably where ICT services, data analytics and a maturing and consumer-friendly IoT provides a higher degree of business and societal transformation, a number of fundamental changes to product design and service delivery need to be considered and made.

The traditional approach to delivering enterprise ICT is being replaced by an approach which recognises that more fulfilling partnerships are a prerequisite if we are to succeed in meeting organisational and customer demands. Cloud computing has provided one such opportunity which allows an ecosystem to be created which spans traditional boundaries—shifting organisational mindsets that others can deliver some core functions more efficiently and effectively than in-house; thus freeing up time and energy to add value elsewhere.

However, to capitalise on this changes to working practices, resource and contract management are required. The IoT provides a useful focus on crystallising the mechatronics challenges of the future as we see these. Consumers and legislators require that all IoT stakeholders recognise when personal and sensitive personal data are being processed, and that their products and services are capable of protecting privacy by design. The IoT will collapse, where consumers do not release their personal and/or sensitive data to device manufacturers and service providers.

The immediate (0–5 years) challenges are therefore:

- Recognising the need to form multidisciplinary partnerships—opportunities to innovate in product design and service delivery will be lost where there is no environment for technologists and information governance and privacy practitioners to come together. Organisations that establish that form of partnership working will be more likely to secure a competitive advantage;
- Establishing new methods of securing and managing user consent—ensuring no economic or functional disadvantage if a user opts out of data sharing;
- Recognising what is and is not personal data in the IoT as processing extends and diversifies in that environment;
- Embedding and responding to privacy by design as a fundamental construct of product and service design.

The medium term (5–10 years) challenges are likely to be:

- Recognising what is and is not personal data in the IoT as processing extends and diversifies in that environment;
- Maintaining a regulatory regime and jurisprudence that protects privacy, without undermining the capacity to innovate;
- Understanding how best to educate and inform technologists, legal/jurisprudence practitioners so that legal and societal demands are capable of being addressed in the development, implementation and application of new technologies.

The long term (10–20 years) challenges are likely to be:

- Understanding how best to educate and inform technologists, legal/jurisprudence practitioners so that legal and societal demands are capable of being addressed in the development, implementation and application of new technologies;
- Quantum computing—to what extent will this alter our perceptions on privacy and technological innovation?

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Chapter 14
Engineering Design for Mechatronics—A Pedagogical Perspective

Simeon Keates

14.1 Introduction

Since the introduction of undergraduate and postgraduate programmes in mechatronics and related subjects in the mid-1980s, there has been a near continuous debate as to the nature and standing of mechatronics both as an Engineering discipline and in relation to its role within Engineering Design [1–5].

In the case of mechatronics education, what has emerged is a wide variety and range of courses structured around the basic tenets of integration concentrated around the core disciplines of Electronics, Mechanical Engineering and Information Systems or Computing but with a wide range of variation and variety to accommodate local requirements and conditions.

Thus, a course developed and delivered in, say, Detroit [6], is likely to differ significantly from one in place in Singapore [7], while both have entirely legitimate claims and arguments to be considered as mechatronics programmes.

Notwithstanding this difference in emphasis, each course will, in general, seek to conform to the requirements of achieving an appropriate level of integration between the core disciplines, with an emphasis appropriate to the overall requirements of the course.

Here, we examine how innovative and challenging mechatronics programmes structured to meet future needs must still incorporate the basic principles of Engineering Design. However, mechatronics remains a fundamentally innovative field and simple instruction in the basic mechanics of putting the components together is missing an educational opportunity to push students to develop their creative engineering thinking. Mechatronics, being such a diverse field, allows students and teachers to explore genuinely innovative questions and solutions. As such, it is well suited to allowing teachers to set tasks and projects for students

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that break new ground and explicitly support the creation of the new concepts and solutions required to take mechatronics forward.

When looking at mechatronics-oriented degree programmes it is necessary to consider how mechatronics is likely to develop and change in the mid- to longer-term future. The goal of any good degree programme is to not only prepare each student to secure their first job, but also to give them the correct skills and mind-sets to retain employment throughout their entire working life. This goal is a particular challenge in a discipline that is as diverse as mechatronics.

14.2 Learning Objectives of Mechatronics Courses

As the name mechatronics implies, the subject is generally considered to be a merger of both traditional Mechanical and Electrical/Electronic Engineering, often with computing elements. However, while knowledge of both engineering disciplines allows students to understand how mechatronic systems function, it is suggested that an essential component of any mechatronics programme is Engineering Design. Mechatronics students are not typically driven solely by grades, although this is an undeniably important motivational factor for the brightest students in particular. Instead, most mechatronics students are more generally motivated by the desire to solve a problem. Any educational programme should be oriented to support this desire and must not inhibit it through too much formulisation. In other words, mechatronics programmes need to support open-ended active enquiry rather than do-it-yourself flat-pack or pro forma type assembly instructions. It is proposed that the key attributes of a graduate of a mechatronics programme are:

• Confidence	• Skills
• Creativity	• An ability to work in a team

Figure 14.1 [5] shows that Engineering Design can be placed at the intersection of a science-based set of skills, the horizontal element of the figure, and social and artistic skills, the vertical element. To these must be added a wider awareness of a range of issues necessary to convert a concept into a viable system or product, such as aesthetics, manufacture, ergonomics and human factors.

In considering the requirements of a mechatronics course with Engineering Design at its core, the essence remains that of balancing the Engineering and IT content within a design focus that supports both individual and group working. The latter is especially important for mechatronics, which is a confluence of very diverse technical domains and thus any one person is unlikely to be a master of all of the technical skills required to build a successful device or system, particularly within the context of developments such as cyber-physical systems and the Internet of Things. In industry, most graduates will be expected to work in a team and so ought to experience the realities of such co-operative work in their programmes.

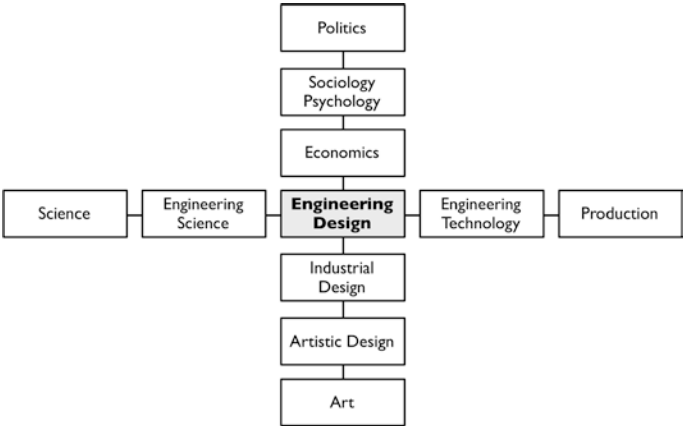

Fig. 14.1 Engineering design issues (after [5])

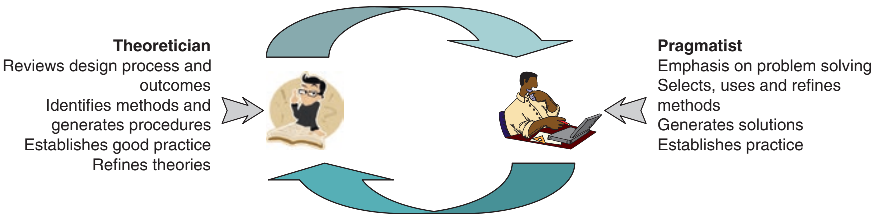

Fig. 14.2 Approaches to design

Key elements here are the need to support communication between members of the group, for instance through computer-based communications structured around the use of digital libraries [8, 9], and to expose students, both individually and as members of a group, to the design process from concept development to implementation [10]. Intrinsic to this is the need to ensure that, particularly in a cross- and interdisciplinary environment, issues of potential misunderstanding through different and differing use of terminology is avoided [11].

Further, it has been suggested [5] that design can be categorised in relation to two broad approaches; theoretical and pragmatic, as illustrated by Fig. 14.2. In practice, these extremes do not exist in isolation, but co-exist along a continuum within the design process. What is perhaps of more significance in relation to course design is that students, inevitably, lack the range of experience associated with established design engineers, and this then impacts on their approach to problem solving [12, 13].

Here, we shall consider issues associated with achieving a design-based input through a combination of project- and problem-based learning linked to mechatronics and looks at these from a range of perspectives including the need to encourage innovation and student perception [14–19].

14.3 The Challenge of Teaching "Innovation"

Innovation and, by extension, the ability to innovate, is a key element of any Engineering Design process and one that needs to be encouraged and developed within a mechatronics course. In the widest sense, the ability to innovate impacts upon issues such as market penetration and the ability to develop, implement and introduce new products to market ahead of competitors, and to maintain that position over time.

Typically, innovation is seen as a continuous and dynamic process involving investigation and feedback across a number of individuals. However, until relatively recently, innovation was considered by many companies as a closed process. An alternative approach, that of open innovation, takes as its goal not simply preserving a current market, but actively seeking to grow and develop other market areas through importing ideas, concepts and technologies as appropriate.

14.3.1 Open and Closed Innovation

Innovation, in all its potential forms, is key to the achievement of new generations of products and systems. In order to develop and take forward the innovative process to meet a new set of challenges, Chesbrough [20, 21] has suggested the need for a shift from the traditional approach, defined as Closed Innovation, with its orientation towards secrecy and the retention of ideas to one of Open Innovation in which ideas and solutions are widely sought from both within and from outside the organisation.

The relationships between these two divergent approaches can be seen in Figs. 14.3 and 14.4. From these, it can be seen that they each represent a significantly different focus on the innovation process, both in terms of the value of ideas

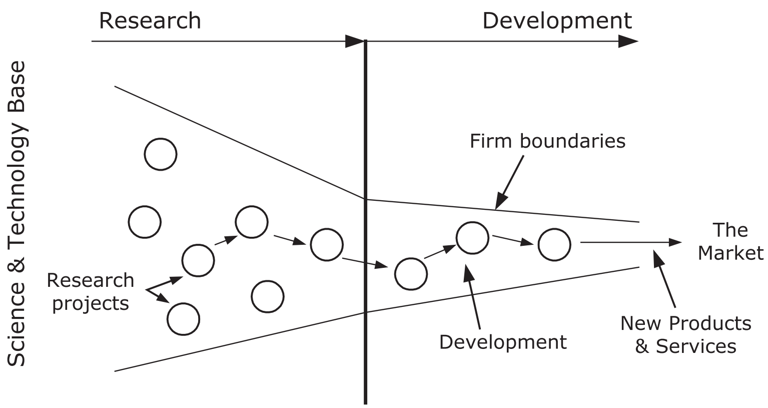

Fig. 14.3 Closed innovation

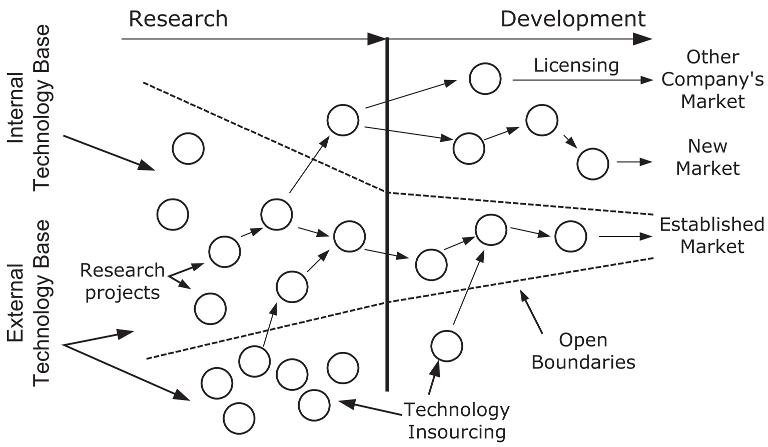

Fig. 14.4 Open innovation

and the ways in which such ideas are to be incorporated into that process. The revised methodology represented by open innovation has been adopted by organisations such as Proctor & Gamble [22] and the US Department of Education [23] to create platforms to develop and take forward new ideas, but perhaps more importantly to bring in new ways of thinking from outside the organisation. Similarly, IBM runs an annual "*Innovation Jam*" as part of its Global Innovation Outlook [24]. Though the underlying motivation, in one case growing company profitability and in the other enhancing an education system, may differ, both are exhibiting a degree of openness by inviting external bodies, groups and individuals to submit their ideas into a central 'pot' for consideration.

14.3.2 Students and Innovation

In 1998, John Prados [25] suggested that Engineering graduates were perceived as having a range of weaknesses, including:

- Technical arrogance
- Lack of design capability or creativity
- Lack of appreciation for considering alternatives
- Lack of appreciation for variation
- Poor overall perception of the project
- Narrow view of engineering and related disciplines

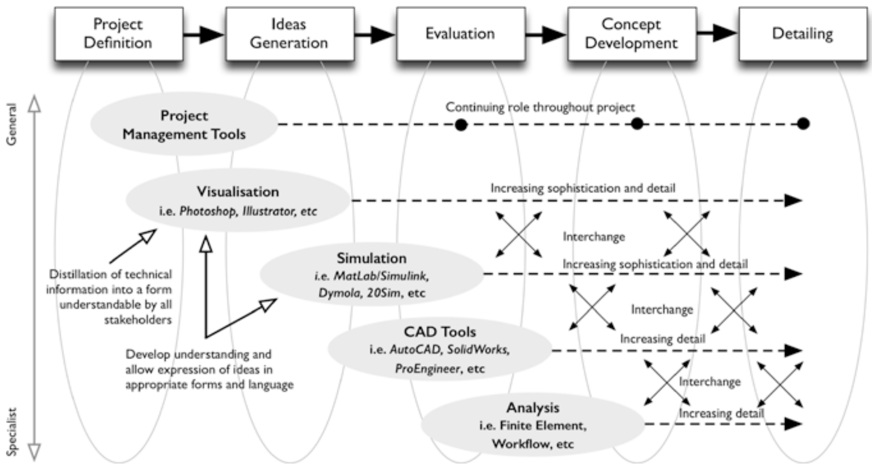

Fig. 14.5 Design support tools

- Weak communication skills
- Little skill or experience in working in teams

In developing innovative thinking by students, all the above issues need to be considered, some of which may well, however, be in conflict with the administrative requirements associated with grading and the ability to differentiate between individual students in assessment schemes [26–32].

There is a range of tools available to support both the design process (Fig. 14.5) and communications between members of the design group [8, 9, 33,34]. In terms of encouraging an innovative approach to design problems, in which the aim is encouraging students to bring forward new and novel ideas, there is a need to create an environment where trying and failing is not considered as a failure in relation to a student's ability to progress or pass the course or module. This means that students are then free to put forward ideas and pursue options in an environment in which the emphasis is on trying and not on failing, i.e.: "*Try and fail, but don't fail to try*".

However, students often focus on the requirements necessary to achieve a particular grade, which in turn tends to lead them to be conservative in their approach as they attempt to ensure that they achieve the necessary marks for the target grade. This conservatism then runs contrary to the requirement to encourage innovation at the expense of an occasional failure to achieve set goals. Thus, insistence on the allocation of a grade, and of differentiating between students, can have a negative impact on the level of innovation.

In this respect, consider student reaction to the essay topic: “*Eli Witney and the origins of mass production*”, which was posed in a manufacturing course. Students were told:

- That there was no predefined or predetermined content required to achieve a particular grade.
- That the emphasis was to be on their ability to source, organise and interpret data available from a variety of sources.
- That in order to obtain a passing grade they were required to demonstrate that they had carried out a level of research and analysis associated with basic information gathering.
- That to achieve a higher grade they were required to demonstrate that they could organise and arrange the information to tell a specific story of their choice using the title as guide.
- The length of the paper.

A comparatively small number of students took advantage of the flexibility to develop a case while the majority took the conservative approach of ensuring they did what was required to pass but then did not feel that they wished to take on what they perceived were the potential risks associated with the achievement of a higher grade.

14.3.3 Choice of Tools

Once a design brief has been given to students, they are then typically given access to a workshop or laboratory for construction of their solutions. The equipment and construction components they are given access to will influence their design process. For example, it is common to use standard components such as Arduino boards and associated sensors [35] or Lego Mindstorms [36] in first or second year mechatronics projects. The choice of which of these components are available will push students down particular design paths. While such provision may simplify the project for the students, as well as keep costs down, it does come at the expense of a level of restriction on design creativity.

One possible solution to the cost issue is the use of computer simulations of components through the kinematic modelling of their properties. An example of such an approach was the variable fidelity prototype developed for the Interactive Robotics Visual Inspection System (IRVIS) [37], which was an accurate model of both the size and kinematic response of robot with five motors and five degrees of freedom—see Fig. 14.6a, b. Such a virtual prototype can be reconfigured, redesigned and completely altered with a few lines of code for absolutely no cost.

The advantages of using a working model that can be adjusted quickly and for comparatively little resource cost when trying to teach innovation are obvious. Students are encouraged to explore different options, because the effort involved

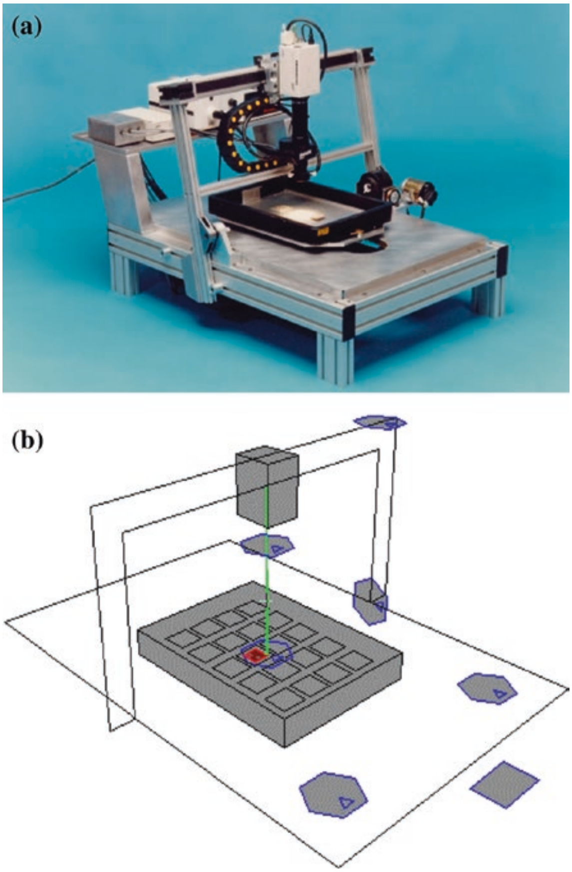

Fig. 14.6 Virtual prototyping in design education, **a** interactive robotic visual inspection system (IRVIS) consisting of a camera mounted on a gantry above a moveable tray of microcircuits. The robot has 5 degrees of freedom. **b** the variable fidelity prototype—a virtual model of the IRVIS robot with authentically modelled kinematic performance

in creating alternative options is minimal and the feedback on the success or otherwise of their design is very quick. However, the model does need to be flexible enough to support more radical design solutions, otherwise what may be intended as a tool to promote innovation may itself become a limitation on that same innovation if students cannot explore and examine all of the design variations they can conceive.

14.4 Approaches to Assessment

As design is generally a group or team exercise, it is sensible to incorporate a group design exercise within a design-oriented mechatronics course. This, however, leads to issues of ensuring that the marks and grades reflect the contribution of the individual members of the group. Strategies that have been used include:

Flat marks	Each member of the group receives the same mark irrespective of their contribution to the final report. This can work if balanced by the internal peer pressures of the group ensuring a balanced level of activity across all members
Individual contribution	Assessing an individual student's contribution could typically involve an agreed introduction and conclusion for which each member of the group would be awarded a shared mark. The individual contributions to the overall project would then be identified and the sections of the report associated with particular responsibility and activity graded separately This approach generally works best where group members have either identifiable skills or worked on clearly demarcated components. The classic example is the development of a robot for following a white line where students can be allocated responsibility for building (i) the robot chassis; (ii) the sensor array; and (iii) the control code
Combined marking	An alternative approach is to couple the project work with an examination that is designed to establish a student's overall depth of knowledge of the project. For example, students are first asked to write a group project report, which is then graded for the whole group. The group is then invited to make an (ungraded) presentation on the report summarising the key findings. The students are free to decide who presents what. This presentation is then followed by individual oral exams, where the group project marks can be increased or decreased by up to one grade Such an approach gives the students an incentive to work well as a group, because they all benefit from a high initial report grade. However, the students feel some degree of confidence that weaker members of the group will be found out in their individual exams and so there is an element of correction in the final grade. Similarly, very able and diligent students also have the opportunity to improve their grade if there had been a problem elsewhere in the group
Peer assessment	Peer assessment can be used in association with either of the above but with a proportion of the marks being held back to be allocated by members of the group to the other members of the group to reflect their perceived contribution Each of the above has been used in association with group projects in design, and each has been met with various degrees of scepticism by students. However, the general view was that the overall marks awarded reflected the contribution by the individual group members A further approach used where groups were competing on the same project brief, as for instance representing individual design groups tendering for a project, was to distribute the reports to other teams prior to marking and asking for a critique of the these to be submitted. These critiques were then graded, with the grade then contributed a percentage of the overall grade. The results from these critiques were generally very interesting, as the majority of teams did not set out to attempt to destroy the other's case, but to genuinely perform a critical analysis of the proposal. Two instances are of particular interest: • One group commented that they wished they had thought of an idea put forward by another group and followed this up with a detailed analysis to demonstrate why they still thought that their solution was superior • Another group commented to the effect that after doing the critique remarked on "*the problems of grading such reports*" and that they had never appreciated these previously

14.4.1 Measures of Success and Success Criteria

The challenge of how to grade such reports is interesting. In any design activity, one of the earliest considerations is that of what measures of success are to be used. Put simply, if two designs are to be compared, what evaluation criteria are to be used? Again there is a range of possible strategies.

For example, consider the classic Civil Engineering student design problem, that of building a structure to span a gap supporting a specified weight at the mid-point. Typical measures of success are (i) whether the structure supported the load; (ii) the weight of the structure; and (iii) the "*cost*" of the structure, which is usually calculated based on the cost of the components and the labour time for fabrication. Most students typically design a traditional truss-type structure, usually a Pratt or Warren truss, because that is what they automatically assume will be the most effective structure. In reality a Waddell-type truss, i.e. a very large triangle design is usually the most cost-effective solution.

A typical mechatronics project is substantially more complicated than this and thus less straightforward to assess, not least because it will necessarily involve multiple Engineering disciplines and multi-skilled teams.

14.5 Teaching Mechatronics—An Example

We have comprehensively overhauled the entire Engineering undergraduate experience at the University of Greenwich. As with many newer universities, the focus of Engineering programmes had typically been on the acquisition of technical knowledge. Consequently, the entire pedagogical experience had been focused on technical instruction, typically in the traditional forms of equations and laws, delivered through lectures supported by laboratory sessions. Assessments were largely exam-based, with traditional mathematically heavy questions where answers were typically either correct or incorrect. Exploration of problem and solution spaces is difficult to encourage in this context.

While the acquisition of technical knowledge is clearly a key requirement of any undergraduate programme, the pedagogical focus on this somewhat narrow goal tended to miss the wider objectives of preparing the students for professional practice. In particular, important skills such as innovation, creativity and engineering "*instinct*", the ability to look at a design and have a realistic view of its merits and weaknesses, were not typically taught. This apparent oversight was not because the academic did not appreciate the value of such skills, more that the programme structure and assessment practices did not lend themselves to supporting them, for the reasons discussed earlier in this chapter. Furthermore, the programmes were delivered in a heavily silo-ed approach, which made the delivery of strongly interdisciplinary subjects such as mechatronics inherently difficult administratively.

Given that we believe that with the rise of notions like the Internet of Things [38], the traditional silos are increasingly archaic, we took the step of completely re-thinking all of the programmes. A number of new degree programmes were introduced, such as Design, Innovation and Entrepreneurship—to help encourage the next generation of entrepreneur–inventors—and Engineering for Intelligent Systems—which is, in effect, a degree in mechatronics.

A new common first year, focusing on the fundamental principles of Engineering Science, was introduced for all Engineering students, whether studying on traditional programmes, such as Civil or Mechanical Engineering, or the newer programmes. The new first year consists of four double-courses:

Engineering mathematics	Students explore a range of engineering problems through which relevant Mathematical skills are taught
Practical and experimental skills	Students are provided with the lab sheets at the start of the year, complete with theoretical primers that are to be completed prior to the lab sessions. The lab sessions then focus on "*learning by doing*", i.e. verifying the theoretical answers through replication in the labs
Engineering professional skills	Students are taught the wider aspects of becoming a professional engineering, such as communication (including essay writing, critiquing, how to précis and presentation skills), risk assessment and management (including the study of engineering failures), ethics and management, among other skills
Design and materials	This consists of some traditional Materials instruction coupled with an introduction to Engineering Design. These complementary topics are then combined into a group design, build and evaluate mechatronics exercise.

An example challenge is to build a remote-control boat. The students are given a budget of £50 and are allocated a material out of which to build their hull. These materials can vary from newspaper to plastic drinks straws or ice cream tubs. A series of challenges for the boats to complete are set, around attributes such as speed and manoeuvrability. For example, in any one year the challenges may include:

- Build the fastest boat.
- Complete the obstacle course in the fastest time and with the fewest penalties.
- Be the most aesthetically pleasing.
- Be the best value-for-money.

Students then have to decide for which challenges to prioritise with their designs.

A possible grading scheme could be developed by attaching values to each of these factors and a simple algorithm implemented to calculate a total "score" for each group. However, once the students become aware of how the scoring algorithm works, this knowledge will axiomatically influence how they approach the design process, thus potentially stifling their creativity. For example, should encountering an obstacle be more heavily penalised than, say, time to complete a traverse, then the students will begin to prefer slow, but steady solutions.

DARPA addressed this issue in its self-driving car challenge [39] where the criterion for success was simply that the first vehicle to cross the finish line wins. A consequence of this approach is a wide variety of highly innovative entrants. Similarly, the *Robot Wars* television programmes had an equally direct approach to establishing the "better" design—a fight until only one robot remained and all opposition had either been immobilised or ejected from the arena. Again, there was a similarly wide variety of innovative designs among the entrants. We are in the process of working with the team behind Robot Wars to establish an outreach programme to local schools to inspire the next generation of mechatronics students by helping schoolchildren design and build robots to compete in Robot Wars.

The solution that we use was inspired by the role of the jury on Robot Wars where a panel of external experts is used to assess each finished design against each of the stated challenges and category champions identified. Those champions then progress through to a final round and a "*champion of champions*" is named as the design that, in the opinion of the experts, best meets as many of the challenges as possible.

14.5.1 In Summary

Engineering Design is a major element of mechatronics and can form the unifying theme throughout such courses. However, the requirement to encourage innovation is often in conflict with the requirements of "quality" and of the need to assign grades to all forms of student-based activity, even when doing so encourages a conservative approach to design. Instead, the aim should be to encourage innovation, and even failure, as to reward students for the adoption of an innovative and a novel approach.

One possible way of accomplishing this is to simplify the criteria or measures of success as much as possible—ideally to a single such metric, e.g. the fastest or the lightest. It is also suggested that all mechatronics programmes focus not only on the development of working solutions, but also on how the solutions fit within the wider environment of use, including their users.

14.6 A Final Note—Do not Forget the User

A common failing among many mechatronics projects is a focus on the technical capability of the device or robot being constructed. This failing is not restricted solely to students; it pervades many mechatronics industrial and research projects. For example, the first iteration of IRVIS project [37] discussed earlier failed to produce a usable robot. The development team had spent 3 years developing the robot and ensuring that it functioned. The interface received scant attention until almost the very end of the project such that when the robot was taken to the industrial test site, the interface was a barely developed version of the testing interface used to drive the motors individually. The final user acceptance test was a failure, because although the user could move each of the motors individually, the visual inspection task required complex simultaneous motor control, which the interface simply did not support.

A second three-year development cycle was required to address these shortcomings. The original development team was replaced and their parting advice to the new team was that the acceptance trials failed because the robot was under-specified and needed a (very expensive) complete overhaul. The new development team instead focused on developing a working interface by focusing on the end tasks of the user. A more complete, task-focused interface was developed and the user acceptance trials were completed with no significant shortcomings being identified. No overhaul of the robot itself was required. The deficiencies in performance suggested by the first set of user trials was a result of the motors not being driven effectively—one at a time instead of combinations together.

The experience of this project is unfortunately common among many such mechatronics projects. In a very insightful paper, Buhler examined the success of several of the major EU TIDE Rehabilitation Robotics projects in the 1990s [40]. His conclusion was that only one of the projects that he evaluated (the MANUS project [41]) had achieved its original design objectives and had achieved a respectable degree of success. All of the other projects were considered failures and the most common reason for failure that was identified was a focus on the technology to the exclusion of almost all other considerations.

Clearly, any mechatronics programme must bear this in mind and ensure that students are aware not only of how to develop such systems, but also how they interact with the wider environment, including their users. Such considerations are routinely taken into account in other specialist domains, such as medical device design and it is suggested that mechatronics students are made aware of such broader approaches to Engineering Design.

IRVIS, as a mechatronics product, was very basic compared with the capabilities of modern systems, such as RoboThespian, shown in Fig. 14.7. RoboThespian has been designed explicitly to mimic human movements and appearance. Final year students are taking up projects to explore how people may wish to interact with the robot and it is straightforward to code and implement lifelike responses. At the same time the success of the IBM Watson system in answering unstructured questions in the Jeopardy!™ challenge [42] shows that "*artificial intelligence*" is developing apace.

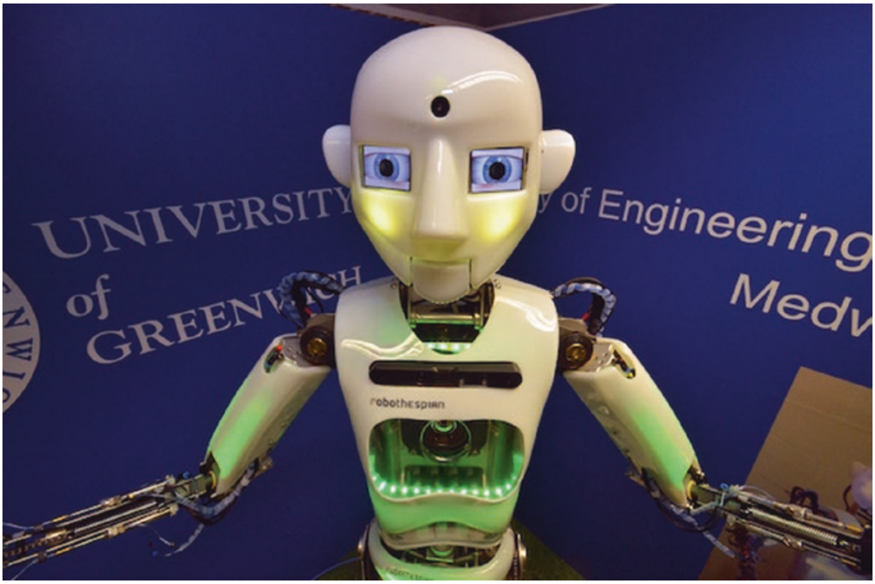

Fig. 14.7 RoboThespian

14.7 The Future

Mechatronics is moving to a future where the design of complex physical components is becoming commoditised, i.e. it is becoming easier to find complex products off-the-shelf, meaning the real area for innovation is in exploring innovative ways to use such capabilities to interact with people.

As we have seen, mechatronics is necessarily a cutting edge discipline where technology is changing rapidly. Humanoid robots, such as RoboThespian, that were the stuff of science fiction only a decade or so ago are now available to purchase. Their cost is still prohibitively expensive for many degree programmes, but similar technologies have shown that an order of magnitude decrease in price is eminently achievable over a relatively short time span as the technology becomes increasingly commoditised.

Indeed, this process of commoditisation is changing much of Engineering and Technology education, as increasingly complex functions do not typically need solutions to be custom built from scratch. Instead, increasingly powerful modular components can be brought together as an assembly, and with the correct settings and control coding can accomplish complex tasks without students needing to reach for the soldering iron.

While it is still very necessary that students understand what goes into each modular component, how they are designed, and what their capabilities and limits are, there is also a growing challenge in terms of the opportunities that are now opening up. The power and potential of these systems means that engineers and designers are now on the verge of being able to think very ambitiously about what they would like their device or system to accomplish, almost unlimited and unrestricted by the capabilities of the hardware. We are not quite there yet, but the capability of the technology is now only a small step behind that of the imagination of the typical Engineering student.

The impact of the next generation of mechatronics devices is already being felt. Take, for example, the rise of 3D printing. In the 1960s and 1970s, companies began to realise that labour costs in the developing world were very much less than in developed countries. The notion of offshoring was born and the following few decades saw the manufacture of low added value products in particular being transferred from countries such as the US and UK to the Far East and elsewhere. However, it is highly likely that the "*no labour*" costs of 3D printers will undercut even those low labour costs, and also have the added advantage that the products can be made at the point of demand and do not need shipping halfway round the world. Once 3D printers and other similar technologies become sufficiently commonplace, the money to be gained in manufacturing will move from those who can make the product most cost effectively to those who can design the most useful or desirable product.

Similarly, the Internet of Things is also an increasingly important development that has the potential to change the world in which we as much as the Internet itself has done since the early 1990s. Again, technologies that are already available are capable of supporting many exciting innovations. However, it is still looking a little like a solution in search of a problem. The only innovations that have thus far gained any notable traction in the market place are somewhat mundane, with elements of home automation, home security and heating applications initially being the most pervasive Internet of Things solutions in the marketplace. Such applications are only scratching the surface of what the technology can support. However, designers and developers are still struggling to find the "*killer application(s)*" that will lead to sufficient homeowners investing serious money in the necessary Internet of Things infrastructure in their house.

Changes in the general population also need to be considered. Many countries in the developed world already have populations that can be considered aged, rather than ageing. There is a clear need for more technology to help support people in retaining their ability to maintain independent living in their own homes [43]. Mechatronics will underpin much of the new developments in telehealthcare, assistive technologies and support for the activities of daily living [38]. However, designing for older adults or those with disabilities involves particular design challenges because of the variety of user functional capabilities [44] that may be encountered as well as different user priorities and goals [45]. Consequently, future mechatronics engineers will need to understand as much about consumer wants, needs and aspirations as they will about, say, different types of motors.

To reiterate what was stated in the introduction to the chapter, The goal of any good degree programme is to not only prepare each student to secure their first job, but also to give them the correct skills and mindsets to retain employment throughout their entire working life, requiring educators to consider how mechatronics is likely to change in the mid- to longer-term future, and how these changes are likely to impact on course content, structure and delivery. This is a particular challenge in a discipline such as mechatronics with all its diversity. The solution must be to aim for a balance between:

- Technical knowledge—Providing sufficient content about the technology of today.
- Underlying fundamental technical skills—Skills such as Design and Mathematics will support graduates throughout their working life.
- Personal skills—These encompass lifelong learning, adaptability, problem-solving and open-mindedness that together make up a flexible and adaptive mindset, open to new challenges.

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Chapter 15
Mechatronics Education: Meeting Future Need

David Russell

15.1 Introduction

Of all the topics feverishly discussed in staff meetings, conferences and blogs, future educational effectiveness and relevance always seems to crop up. Professors, remembering their own education and struggles to attain their current status in academe bemoan the current lack of mathematics, the lack of student talent, and the drift away from hard design to a plug-and-play mentality. There are evident disjoints between Software-as-a-Sservice (SaaS), cloud computing, and Platform-as-a-Service (PaaS) and mechatronic systems.

While abstraction from the internals of the computational units that constitute the Internet of Things (IoT) might speed up product launches, the mechatronic engineer who is operating in the actual application domain is left pondering the integrity of the software and its source, its ruggedness over time in the real world setting, how to manage component upgrades, and the recovery of the system after a failure. This chapter includes true vignettes, disasters, challenges and discussion topics from the author's experience, selected to highlight what a mechatronics engineer must know and to illustrate the necessity for innovation and technical dexterity. Each subsection of this chapter is chosen to highlight technical and non-technical topics that should be integral to mechatronics education long into the future.

The author was an invited panel member in the vigorous discussion at the Mechatronics 2014 conference held in Karlstad, Sweden in June 2014. He has worked in the manufacturing systems integration industry and academia for almost fifty years. The views expressed in this chapter are his alone, and designed to provoke discussion and hopefully bring about real advances in mechatronics education among teaching staff and administrators in the institutions of its readers. As educational delivery mechanisms migrate from the traditional lecture-recitation

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classroom in favour of more outcome-based syllabi and technology-enhanced learning, it is hoped that the reader will be able to decide upon the best course of action to take for mechatronics and similar discipline courses of study.

15.2 The Educational Experience and Employment

Taking a rapid global scan of the educational process, it is obvious that there is no real *body of knowledge* of mechatronics as opposed to say the medical profession. It is not within the purview of this chapter to compare countries with countries, universities with universities or even precollege common core education. The objective is to highlight how differently somewhat similar materials can be taught to the students who constitute the future engineering cohort yielding to the inevitability of on-line delivery.

While on-line instruction, at the time of writing, may be in an ascendancy, the *Center for Teaching and Learning* at the University of North Carolina Charlotte (UNCC) [1] lists 150 different teaching methods, admittedly not all of which apply to mechatronics. These range from the well-known “*lecture by the teacher*” which appears as #1, to “*small group brainstorming*” listed as #150. Buried as #106 is “*the use of technology and instructional resources*.” At the risk of being facetious, the chapter author’s favourite is #127 “*visit an ethnic restaurant*.” But, what is best for the student?

There are many instructional methods. Table 15.1 is based on a College of Southern Nevada (CSN) website [2] and summarizes some of the instructional methods that can be affiliated with the various teaching styles.

Academic readers will readily associate how classes at their institutions are conducted in the main. Following the full CSN website, the interested reader may find how these methods translate to an on-line environment interesting.

15.2.1 The Institution

In the US, there are over one thousand colleges and universities that boast having an engineering school. This number is increased significantly if the number of engineering departments in Europe, China and India are added. Most schools are regulated by governing bodies (e.g. ABET in the US) as far as the curriculum is concerned, but there is no common core curriculum for the nation.

This means that what is taught at Institution A may be covered superficially or not at all in Institution B. Overseas, the problem is worse. Some engineering schools in certain countries do not pass muster outside of the country itself. By awarding *engineering* degrees such institutions promise good jobs and better lives for their graduates only to not even be considered for a good job inside or outside the country. This is not good for the student.

Table 15.1 Instructional methods and teaching styles

Method	Comments
Lecture	A flexible method which can be applied to almost any content. Although lectures can be very engaging, they put students in a passive role. Experienced staff members can interweave their real-world experiences into course materials to show the relevance of the class **Teaching Style**—*Formal Authority*
Lecture-discussions	Combines the lecture with short question periods or a series of short question periods for students **Teaching Style**—*Formal Authority*
Demonstrations	Involves students learning a process or procedure based on instructor performance. The students may be involved in the demonstration and practice **Teaching Style**—*Demonstrator*
Simulations	Simulations put learners into seemingly real situations where they can make decisions and experience the outcomes of their decisions without the risk **Teaching Style**—*Facilitator/Delegator*
Collaborative learning	Students process information and derive knowledge through discussing course-related issues and topics with each other **Teaching Style**—*Facilitator*
Cooperative learning	Small groups of students work together to solve a problem or complete a task **Teaching Style**—*Facilitator*
Case studies	This involves individuals or groups of students working together to analyze a case, which is customarily a real-life situation which has been written up to highlight problems and solutions **Teaching Style**—*Facilitator*
Role play	Students work to solve problems through adopting the different roles associated with it. Role play involves identifying, acting out, and discussing problems. With care this can be highly effective especially in the non-technical aspects of systems engineering such as human resource management **Teaching Style**—*Facilitator*
Problem based and inquiry learning	Instructors give students a problem which the student must solve by gathering data, organizing data, and attempting an explanation. Students should also analyze strategies that they used to solve the problem **Teaching Style**—*Formal Delegator*

To rectify this problem, many well regarded colleges and universities are populating on-line and residential post-graduate courses. Mechatronics, robotics and other disciplines are popular topics in what are intended to be *educational objects*.

15.2.2 The College Faculty and Staff

University teaching staff, instructors, and professors ideally are mature and have some actual industrial experience. With no real pedagogic training, they teach as they were taught, with much theory and arguably little relevance to their students interests or final occupations. Most teaching staff have had little or no formal training in teaching, classroom management, or legal and ethical matters.

US News and World Report ranks the top schools annually but this ranking generally reflects research expenditures, the number of doctoral degrees awarded if appropriate, a tally of staff who hold a terminal degree and Fellow status within their institution. The rating may include graduation and retention rates. Teaching may be prescribed for each staff member, but it is certainly held in lower regard than funded research in contract renewal matters.

Efforts such as the UK Teaching Quality Assessment (TQA) were designed to highlight and reward good teaching practice at schools and colleges in much the same way the Research Assessment Exercise (RAE) handles research. It is the responsibility of university staff to perform both research and teaching well to promote high marks in both the TQA and RAE reviews. In the US, engineering departments are subject to a periodic nationwide ABET accreditation process but only at the baccalaureate level. But, what is best for the student?

15.2.3 The College Student

In the US for example, many engineering students spend just over two years in fairly focussed programs (e.g. electrical engineering) and may select their major while in their first or second year. Concurrent with these studies, students will be exposed to ethics, legal issues and presentation. In Europe, students may enter programs already knowing their chosen field and experience four years of topical study. Some schools inject a term of work experience before their final year while others engage final year student projects.

It almost goes without saying that successful students will have good study skills and an excitement about engineering while lackadaisical students tend to do poorly and often transfer into other (self-perceived as easier) programs or institutions. It is a well-known construct that how a student learns about Science, Technology, Engineering and Maths (STEM) before college is a major indicator as to what fields of study the college-bound student selects; this varies globally as will be shown at the end of the chapter. Despite scholarships and financial aid, location, need and social status do figure as to which institutions are feasible to an applicant.

Engineering schools worldwide are somewhat selective and require four or even five years of study for a baccalaureate degree. Mechatronics is certainly taught at the baccalaureate, masters, and doctorate levels but usually championed by enthusiastic staff. Are students attracted to post-graduate degrees to help staff with research and teaching rather than industrial employ? Is this best for the student?

15.2.4 The Mechatronics Employer

Imagine now that the student has successfully managed to gain employment in a technical company that for the sake of this chapter produces or uses mechatronic systems. Such employers have a perceived need for expertise to further their product or service and have high expectations for the incoming graduate or technician.

In the legal and medical professions, novitiates must complete residencies to become certified before being allowed to practice, whereas in engineering chartered membership in an institution is considered largely optional, expensive, and irrelevant. It is common practice for new employees shadow experienced engineers until they can be assigned to projects experts in their own right. From this, the reader can deduce why projects fail, how cost overruns happen and products never quite work as anticipated by the client. What is best for the company?

15.3 Mechatronics: A Selection of Real World Vignettes

The following contains three factual real world vignettes from the chapter author's experience designed to reflect necessary topics in mechatronic education. The corporation or company names are omitted for confidentiality reasons but hopefully the reader will find the examples useful. Each subsection will briefly describe a real system and how it was designed, how a problem presented itself, the resolution of the problem, and most importantly, what educational skill enabled the mechatronics engineer to address the problem. The first case is given in much more detail than the other two to better illustrate the point.

15.3.1 An Injection Moulding Monitoring System

Overview

An injection moulding corporation is contracted with a systems engineering company to design and implement a production monitoring system for its main location that operates up to 40 high-tech moulding machines. About 35 machines run regularly on any one day producing several tens of millions small plastic parts daily. The components are packed in boxes by weight and passed on to quality control and inventory. Figure 15.1 shows a typical injection moulding (IM) factory.

Fig. 15.1 A typical US injection moulding operation (*Courtesy of the Rodon Group, Hatfield PA*)

The factory manufactures a variety of items on a job-by-job basis. A job change on any machine requires much effort in purging the previous, coloured raw materials and the necessary mould mounted, and new liquid plastic bled through the system for the next job. The mechanic may cycle the machine many times until the new part is perfect, but these test operations should not ever appear in the production count.

Summary of Requirements

Without going into further detail, the requirements of the system included the measurement of each cycle of each machine on a 24 × 7 basis, a comparison of actual performance with the factory work order, the provision of display screens throughout the factory and the periodic download of inventory data to a mainframe computer. From a data integrity standpoint, this is actually very difficult to do because not all machine cycles produce product, e.g. a technician loading a new job or clearing a mould jam.

System Design

After meeting with the industrial client several times, Fig. 15.2 emerged as the preliminary system design. The major components are fairly standard in most industrial automation setups. The programmable logic controllers (PLC) are industrial process control agents which are resistant to power outages and are available with local storage, communication capabilities and multiple input and output data ports.

Having designed the system the following hitherto unforeseen questions were posed after a more detailed system site inspection:

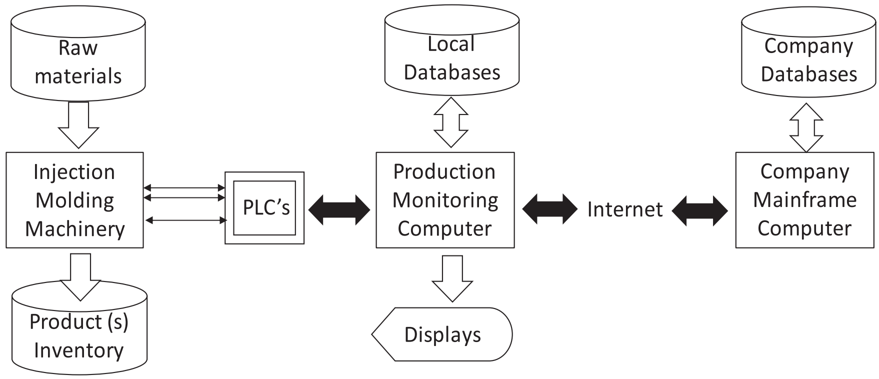


Fig. 15.2 Preliminary system design

1. How to connect machine information over long distances? The factory is over a mile long.
2. How to connect all of the system devices over such long distances? Electrical signals were all low quality with much apparent noise being generated randomly from the injection presses.
3. How much information is it useful to display?
4. How can operators and mechanics provide specific data for display?

Once these matters were resolved, which in fact did involve some redesign of the system and the purchase of additional software and hardware, the system was coded and installed.

Problem Areas

In the day to day operation of the system, the following unexpected situations arose:

1. What appeared to be random data freezing anytime during operation.
2. Data loss after a blackout or brownout of primary factory power.
3. Handling machine maintenance and repair status cycles.
4. Shift reports show incorrect times.

These problems seemed to indicate fatal flaws in the system, yet were solvable using mechatronic principles. The chapter author's solutions are summarized in Sect. 15.5.1.

15.3.2 Executing Mainframe Code on a Minicomputer

Overview

A company was using a mainframe computer for advanced CADCAM and graphics. Each design station cost over $50,000 and the mainframe lease and operating system was over $100,000 per month. The consultant found a company that had found a way to run instructions from the mainframe on a $20 K minicomputer by making some minor adjustments to the motherboard of the minicomputer.

Overview of Invention

Figure 15.3 illustrates how the mainframe instructions were accessed and executed by the minicomputer by modification of the minicomputer motherboard with proprietary firmware. The schematic blocks shown dashed were the only firmware modifications needed. The minicomputer word size must be comparable with the mainframe instruction chip set (32 bit) which was purchased from the manufacturer.

Problem Area

The system functioned very well and the CADCAM application was successful and an inexpensive alternate to the traditional graphics workstation. One day, after a minicomputer operating system upgrade, the system completely failed to operate. Mainframe computer instructions embedded in the CADCAM sequences suddenly caused the minicomputer to return an illegal instruction trap and a complete CADCAM failure.

This problem indicated a fatal flaw in the system that eventually proved unsolvable causing the project to be discontinued. The chapter author's explanation is summarized in Sect. 15.5.2.

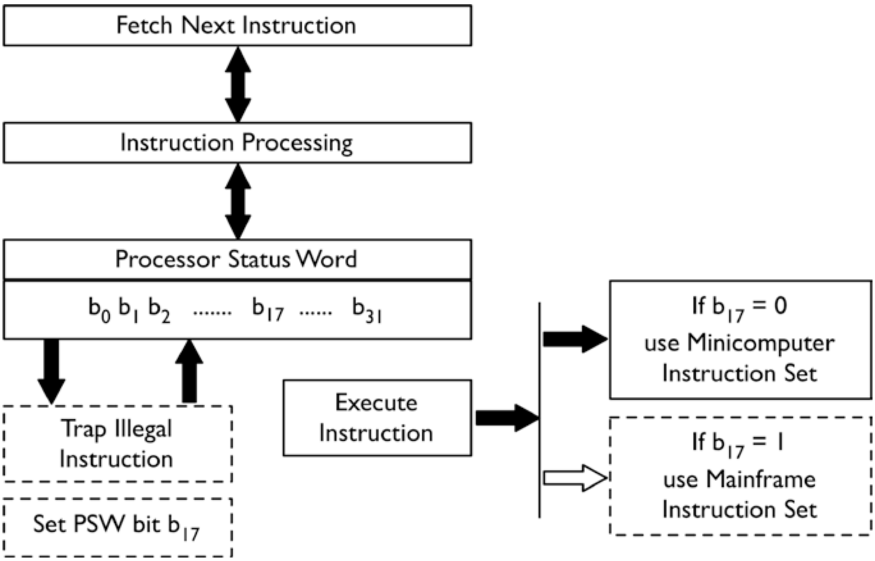


Fig. 15.3 Modified minicomputer motherboard schematic

15.3.3 A Mechanically Unstable System

Overview

Many researchers have studied various methods of inducing control into an inverted pendulum rig. This system lends itself to adaptive, intelligent, evolutionary and learning control. Figure 15.4 is a photograph of one such rig with which the author worked [3]. Essentially, the cart was driven in bang-bang LEFT/RIGHT mode on computer command. The experiment was bounded on a two meter track with crash sensors at each end. The pole on the cart was freely hinged but limited to about $\pm 10°$. If the system went out of range, the motion on the cart was stopped. The problem was to balance the pole by moving the cart left or right and should not be confused with the swing up pole balancing act.

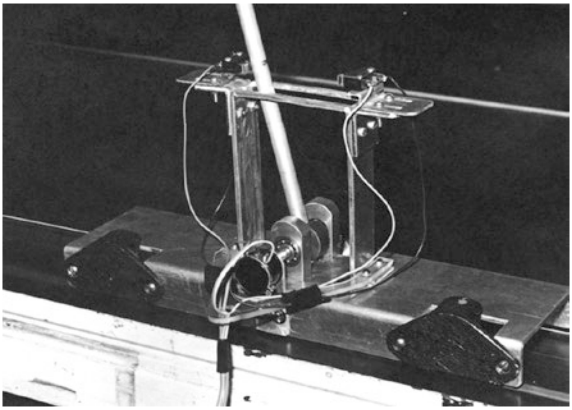
Problem Areas

The two major problems were ensuring that the system engaged its learning algorithm from an initial random but legal state so that the controller could recognize it and launch out on a control excursion, and handling slippage in the driven wheels when the cart direction was reversed. The chapter author's explanation of a solution to the first problem is summarized in Sect. 15.5.3.

15.3.4 Summary of Cases

For each of the above three cases, how these problematic situations were addressed appears below in Sect. 15.5 to encourage readers to discuss their own ideas with those of their students before reading that section. After reading the author's comments, readers should discuss then what educational modules at their institution or company would have enabled the novitiate engineer to address those problems?

Fig. 15.4 A trolley and pole experimental rig



Perhaps the missing educational experiences in our colleges and universities are in-depth coverage of systems engineering and system integration.

15.4 Systems Engineering and Systems Integration

In the cases given above in Sect. 15.3, it should be apparent that the designs of the system components, the integrated system, and even the placement of the system within its global domain (a.k.a. in a system of systems) rely heavily on the understanding of systems engineering and systems integration.

15.4.1 Systems Engineering

Perhaps the clearest definition of systems engineering is found on website [4] of the International Council on Systems Engineering (INCOSE) from where the following quotes are taken:

> (INCOSE) … represents systems engineering professionals from industry, government, and academia worldwide. It strongly believes that the fundamental principles of systems engineering have an important role in the education of all engineers, regardless of their specialty, as well as professionals who work with systems engineers but do not have an engineering background.

The same website explains the nature of the discipline and its truly outcome-based focus.

> Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

Specifically, systems engineering is an integrative paradigm that for many years was never taught in engineering colleges, assuming that graduates of their programs will pick this up later in their careers.

> Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

15.4.2 System Integration

System integration is a well-known subject in computer science and IT and has come to mean the assembly of software systems using *plug-and-play* paradigms from software located as COTS (*Code off the Shelf*), SaaS (*Software as a Service*) and of late Cloud Services. In the software realm, the major integration issues in an open architecture environment are system and application configuration. In this activity, the integrator has to skilfully slot the application into sets of code that may have been written externally in another language. Enterprise software systems such as SAP® require the use of many configuration forms and data manoeuvres before a manufacturing company can benefit from its complexity and information power. Most problems arise from hardware failures, internet issues and misfits in terminology and usage.

In mechatronic engineering systems integration problems arise from combinations of mechanical, electrical, computer and systems disciplines. Solving in one area may cause sudden failure on another front. The second Sect. (15.3.2) is an illustration of how a project failed through no fault of its own as explained in Sect. 15.5.2. It was actually the reluctance of the minicomputer vendor to make a simple revision to their operation system that caused the failure.

Computer engineering and computer science programs usually include some information integration, database and internet-enabled modules. Formal engineering programs by and large contain very little curricular coverage of system integration. Warminki and Ikonomov [5] opine that: *"… the basic engineering curriculum fails to teach valuable skills in the areas of*:

- *Knowledge management/documentation/recall and reuse.*
- *Working in cross functional distributed teams.*
- *Critical thought in the framework of product design.*
- *Design methodology including: translation of vague requirements to engineering specifications, failure mode identification and effect analysis, total parameter and tolerance product design, manufacturing execution, function as a member of a team to undertake the analysis and integration of automated manufacturing processes."*

This issue at their institution is being addressed by a detailed hands-on project in which students are posed with real problems to solve. In a group situation, students can engage in problem solving activities such as Scrum [6] and other similar team oriented project work.

15.4.3 Hands-on Versus Knowledge-Based Instruction

This project-based approach introduces the controversy of the educational value of hands-on "*tinkering*" by students versus a traditional solid educational classroom instruction. The popular vogue of "learning by doing" may work well in simple classroom situations, but would it work in the cases given above in Sect. 15.3? Can an impatient, paying, client be expected to wait for expertise to be learned? Section 15.2.4 is understated.

Formal engineering programs especially those under accreditation control are loath to forfeit more classical topics in favour of mechatronics or systems engineering. Many schools have introduced one or two year taught master's programs in mechatronics. These are more popular in the US than in Europe. In all, it is the experience, enthusiasm and focus of university staff that are charged with the trust of producing ethical, worldly wise competent engineers of all disciplines. Much project work is undertaken on an individual level with little interface with other students, whereas in industry the ability to work in a team is a much sort after skill.

15.5 Solutions and Educational Sources to Case Issues

The following are outlines of how the problematic areas of each case were resolved, but readers may want to discuss other solutions with their colleagues and classes. Much more detail is given to the first case to illustrate the complexity of mechatronic systems and because it was housed in a real-world industrial environment. The second focussed on the need for a fairly deep knowledge of operating systems and firmware, and the third on mechanical design and the use of timed software.

15.5.1 An Injection Moulding Monitoring System (Case 15.3.1)

The solutions to the problems introduced in Sect. 15.3.1 are summarized below but it should be clearly understood that this is not an exhaustive list.

Problem (a) and (b)
These questions focussed on the long distances connecting devices and the low quality and high noise electrical signals.

Solution—The use of shorthaul modems and a check on all wire shielding in the factory roof helped with this problem. A better, if more expensive, solution would have been to rewire using fibre optic cables.

Educational Objects—The engineer needed to be conversant with modems, communications and fibre wire connections over long distances.

Problems (c) and (d)
These introduced the issue of good data collection, displays and factory floor inputs.

Solution—It is essential that a focus group that includes the industrial client and factory floor personnel decide what data is to displayed on the shop floor. It became apparent in the system in question that shop floor data needed to be collected from the operators. This data then identified the need and nature of a machine breakdown, etc. It was necessary to instal microterminals and integrate this data into the database using data fusion techniques.

Educational Objects—The system designers needed a deep understanding of database design and fusion, and human computer interaction.

Problems (e), (f), (g) and (h)

These all occur during the operational phase of the system from time to time. In the original system, the data collection and all database operations would freeze mimicking the effects of a power outage.

Solution—The design and implementation of the factory software required a level of system intelligence so that temporary problems and failures could be detected and "self healed" to avoid loss of data. The actual system included programmable logic controllers (PLC) in which front end intelligence was embedded to temporarily store data during a system pause or stoppage.

Educational Objects—The mechatronics engineer needed to understand file locking and system programming to free locked files and folders. Real time operating system design knowledge is essential as was a familiarity with available industrial components.

15.5.2 Executing Mainframe Code on a Minicomputer System Failure

How the system works

Figure 15.2 depicts how the proprietary firmware purchased for modification of a minicomputer motherboard utilizes an unused bit 17 in the minicomputer's 32 bit processor status word (PSW). The operating system kernel allowed system users to access all PSW bits in high priority tasks. Included in the PSW is a bit 3 that traps an instruction error. It was this bit (bit 3) that is set when the minicomputer attempted to execute a mainframe instruction. If the executive program detects such an event, it sets what was the last unused bit (bit 17) that was designed to direct execution to the additional hardware for execution.

Reason for failure

The minicomputer vendor issued an update to the operating system that innocently used that bit (17) for a new elaborate print function. The operating system software team had spent many hours developing this new function that would benefit all of its other customers. The CAD/CAM project was cancelled.

Educational Objects—For the mechatronic engineer to detect, this would require a fairly high level of computer architecture, systems programming, and firmware. As an aside, advanced negotiating skills might have saved the project!

15.5.3 A Mechanically Unstable System

Randomized but Legal Initial State System

Many pole and cart systems begin with the pole being held vertically near the centre of the track. Upon release, the system is engaged and the process proceeds but always from nearly the same initial state variable values. This is a real flaw in the system. In the case in question, in order for the trolley and pole logic to engage its learning paradigm from a random but recognizable initial state, it was necessary to construct a startup subsystem that drove the cart in one direction for some random time and then reversed the cart direction for a shorter random time and then reversed it again. This would jerk the pole from its initial steady state resting position into a dynamic state but will not allow it to gain enough momentum to fail. During the startup process the control system monitored the state variables When the starting system entered a state in which the system's bang-bang controller value coincided with the startup value, the startup logic was disconnected in favour of the system.

There many other such examples where readers may choose to insert their own examples from their own experience using this approach.

15.6 Conclusion: A Global Problem with Local Solutions

Addressing future educational methods "*The answer is not to be found by looking in the rear view mirror*" So states Marshall McLuhan quoted in a recent *Educause* article by Brown [7]. Brown discusses concepts such as Adaptive Learning Technologies, Learning Spaces, Learning Analytics, and Next Generation Learning Management Systems and focuses on how students must navigate a way through a pathway or *swirl* of instructional experiences.

This certainly has elements of truth but might be an oversimplification. Engaged faculty who are able to bring their research or other technical interests into the classroom can not only hold the attention of their class, but also create a learning environment that causes students to be life-long learners, ethical, and innovative. Looking again at Sect. 15.5 where plausible (and actual) solutions are listed, readers should consider where these skills are being taught at their own institutions.

This matter is not limited to North America or Europe, but is a global malaise in what are often classified as *good* institutions in China, India, Singapore, Australia and many other countries.

A ready solution might be a better understanding and use of continuous professional education (CPE) modules such as offered by universities and the professional institutions such as the IMechE, IET, IEEE, ASME and the like. Such programs can help retrain more senior engineers as well as fill in the gaps in new hires. For a deeper coverage of mechatronics many institutions are offering taught masters programs which can be face to face or on-line. In these programs, students are already degreed engineers and therefore can focus on mechatronic issues such as described in this chapter without much mathematical or basic engineering review.

The intent of this chapter has been to introduce some concepts of how mechatronic systems posit a variety of problems for which students, even at the doctoral level, may have had no in-depth instruction and who do not yet possess the savvy of an experienced engineer. Reference to statistical data has been largely avoided as numbers change so rapidly from year to year and are provided by unreliable sources.

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Chapter 16
Conclusions

Peter Hehenberger and David Bradley

The authors hope that readers of the book have enjoyed the fundamental research topics and future visions of the contributors to the text. This chapter reflects the interaction and integration of these major topics and tries to summarize the key statements.

It should be pointed out that the continuous (r)evolution of the technical (mechatronic) systems with the deeper integration of multiple disciplines (e.g. IT functionalities and components) and the detailed consideration between the products and their related production processes are parts of the major trends in product design. Furthermore, the involvement of several partners (all over the world) and the challenges of new business process play an important role.

16.1 Global Trends and the Impact on Mechatronics

An overview on global (mega) trends has been provided by several institutions in recent years (e.g. see [1]). They differ from each other in detail, but the major topics are involved in all published studies as follows:

- Demographic change (and ageing society, healthcare systems)
- Mobility
- Globalization (and changes in the work world, economy, finance)
- Urbanization (and individualization)

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- Climate change and environmental change (and Energy and resources, sustainability)
- Knowledge-based society (and ubiquitous intelligence, digital culture)

For manufacturing production in 2030 the following four major topics are discussed by Westkämper [2]:

- Innovative products and processes
- Knowledge-based manufacturing engineering
- New business models in the life cycle of products
- Infrastructure and education

The result of all these trends is also that the technology has to push forward. So there are high product development potentials in mechatronics due to the combination of multiple disciplines, as discussed in the chapters of this book.

One major part of economic success is the development of innovative products and processes. The term innovation comprises invention, introduction and sales of a new product, service or procedure [3]. This does not only include the whole marketing process, but also the social and economic impact. Irrespective of the quality of the invention many, factors influence the growth of an invention into an innovation. The main factors discussed in this context can be split into three groups of technological, economical and social influences (see global trends [1, 2]). The field of mechatronics is known to be the source of numerous innovations. However, most new developments are identified as incremental innovations. Conceptual design has been identified as the most critical phase in product design in context with radical innovations as the main portion of success will be established there.

Decisions made in this early stage have a superior influence on the future development of the product. Therefore, the definition of the requirements on the system level for the overall product is crucial. The requirements which are defined on the system level should reflect the customer's wishes. To ensure that the system under consideration meets the requirements, it is necessary to translate them into properties of the solution. The development of systems merges solutions from disparate engineering disciplines, like mechanical engineering, electrical engineering, control engineering, etc. So it is very important to distinguish between properties which can only be assured on the system level and those which can be assured by a single engineering discipline. Hence, it is important to assign the different properties to the relevant level [4]. For achieving this task models on the different hierarchical levels are necessary (discipline-specific model and system models). From this point of view the modelling, simulation, evaluation and optimization of the considered specific aspects are key points for future mechatronic systems design, as is also mentioned in several of the previous chapters.

16.2 Mechatronic Futures Map

It is understandable that it is not possible to discuss all aspects of *Mechatronic Futures* in “one” single book. The goal in this book is how to group the challenges into main subjects and present specific aspects from different viewpoints. The common viewpoints and perspectives are identified below, while Fig. 16.1 shows the map of the following topics:

- *Issues and Challenges*
  The main driver for future evolution of mechatronic systems is the reduction of development costs and time as well as the improvement of the designed products using new technologies. This deals mainly with the virtualization of the product to improve its architecture design, its verification and validation, its production or operation. Indeed, virtualization enables more flexibility in the different stages of the development at lower cost. The interaction between the designed product and the production systems plays an important role in the direction of Industry 4.0 (or Smart Manufacturing, Cyber Physical Production Systems, etc).
- *System Design, Modelling and Simulation*
  Mechatronic products gain a more complex structure and will have more computing power and network connectivity. This leads to the extended design challenges in understanding the difficulties of complex systems where simulation will be a

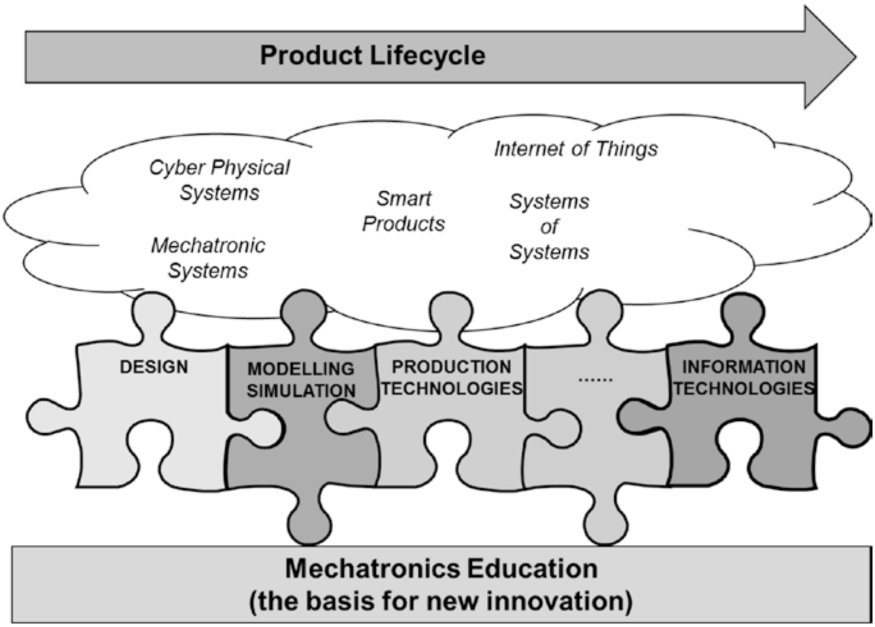

Fig. 16.1 Mechatronic futures map

key technology for mastering these. The future trends, methods and models for the design processes of mechatronic systems have to be considered as unquestionable enablers for transformation of complex systems into cyber physical systems or the global integration of the internet of things. These design processes for mechatronic engineering have to support the development of the new services or the implementation of an industrial internet for the factories of the future.

- *Manufacturing Technology*
  Future technologies (e.g. Additive Manufacturing or AM) for physically creating mechatronic devices and systems will enable new possibilities in the design process. There will be a shift from "*design for assembly*" approaches to "*direct manufacturing*" approaches. So we could remove the need for post-fabrication assembly and use of fastenings, yielding rapid production of robust devices. Nowadays typical examples are 3D printed sensors, 3D printed electronics and integrating multiple materials, which is the basis for the production of "*Fully Integrated Mechatronic Devices.*"
- *Internet of Things and Cyber Physical Systems*
  The current trend in mechatronics involves the deeper integration of computation and physical processes in networked mechatronic systems, cyber physical systems (CPS) or Internet of Things (IoT). Therefore communication, integration and data analysis are considered essential since the scope for IoT will depend upon the consolidation of diverse systems and standards, with "*lower level*" (local) systems talking to each other and to "*upper level*" (global) systems. Typical applications are home automation, production, transport, energy, health care and agriculture. The lauded potential social and economic benefits are plausible but not guaranteed yet.
- *Communication and Information Technologies*
  The key issues here are associated with the need to facilitate the formation of multidisciplinary partnerships. Without such partnerships, opportunities to innovate in both product design and service delivery may well be lost. Consequently, organizations that establish robust forms of partnership working are more likely to secure a competitive advantage. Associated with this is a requirement to establish new methods of securing and managing user consent, while ensuring no economic or functional disadvantage if a user opts out of data sharing.
  This leads in turn to questions as to how to educate and inform technologists, along with legal/jurisprudence practitioners, so that legal and societal demands are addressed in the development, implementation and application of new technologies.
- *Mechatronics Education*
  Mechatronics is moving to a future where the design of complex physical components is becoming commoditized. The particular challenge is that of subject diversity and mechatronics education must therefore aim for a balance between "*Technical knowledge*", "*Underlying fundamental technical skills*" and "*Personal skills*" and any educational programme should be oriented to support these areas. Typical topics, which have to be covered by mechatronics courses

are aligned along the product life cycle, including innovation, creativity, systems thinking, engineering and integration used a combination of project- and problem-based learning methods. Mechatronics education is then the base for applying newly available technologies.

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