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A Design-Oriented Undergraduate Curriculum in Mechatronics Education*

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Mechatronics is bringing about an industrial paradigm shift with its multidisciplinary integrated approach to product design and development. It is poised to become the key enabling technology to use for gaining a competitive edge in the modern manufacturing era. The development of mechatronics will therefore be crucial to the continued competitiveness of national economies. In order to fulfil the changing requirements of industry, many universities worldwide have introduced course revisions and new courses in mechatronics. In the present paper, an attempt has been made to redefine mechatronics and synthesize various mechatronics programs being conducted all over the world. The proposed curriculum envisions mechatronics as a new engineering design strategy, perceives it as a systemic business philosophy and emphasizes interdisciplinary communication, team effort and industrially relevant project-based learning.

INTRODUCTION

WITH AN ever-accelerating pace of change in industry, rapidly expanding technology access, fast improving information and communication systems, globalization of markets and business competition, resource limitations and ever rising customer expectations, engineers have had to adopt a new way of doing business. The pressing need for increased productivity as well as for the delivery of end products of uniform high quality is turning industry more and more towards computer-based automation. As a synergy of core technologies—of mechanical engineering and electrical engineering, electronics and computer science and instrumentation and controls—mechatronics is fast becoming an important component of modern products and processes that are highly integrated in functionalities. A new concurrent engineering thinking framework in the process of designing complex machines [1], mechatronics is indeed bringing about an industrial paradigm shift. In fact, mechatronics with its multidisciplinary integrated approach to product design is poised to become the key enabling technology for gaining a competitive edge in the modern manufacturing era. The development of mechatronics will therefore be crucial to the continued competitiveness of national economies.

Growing need for mechatronics education

The history of mechatronics has been well described in [2]. In recent years, the ever increasing use of microcontrollers and microprocessors in an extremely wide variety of consumer and commercial products, laboratory test instruments and equipment, and industrial applications has necessitated a need for mechatronics education in all engineering disciplines. Many universities worldwide, especially in USA, Europe and Asia have introduced course revisions and new courses based on this discipline. [3–11]. Besides, in order to achieve mechatronics education in various engineering fields, educators have experimented with several approaches in the past. The goals, approaches and emphasis of mechatronics courses generally depend on the discipline and level (graduate or undergraduate) of students and duration for the course. With the spread of mechatronics to all kinds of engineered products and systems, however, it has become imperative that a whole new stream of engineering be initiated to impart education in its principles and practices.

Industry requirements and expectations

The specialist mechatronics engineers are expected to be able to adapt quickly to the trends in industry, to respond quickly to the needs of the market and to adopt an integrative approach in product and process development, and by virtue of their knowledge and/or experience in various disciplinary skills, be more competent team leaders. The mechatronics engineers would be required to work confidently in an industrial environment deploying advanced technology according to mechatronics principles as well as communicate with and provide a link between specialists in particular areas of technology within a team working environment such as that required by concurrent engineering. They would also be able to make significant contributions in all stages of engineering design—from conceptualization to final product design—in a truly systemic approach wherein electrical, electronic, computer and

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mechanical subsystems are simultaneously designed to function as an integrated whole, as a single system.

Objectives of the paper

Whereas traditional engineering curricula tend to be science- or analysis-based and keep a student focused as an individual within a particular discipline taught by only one department with little industrial exposure, mechatronics needs to reject such a rigid compartmentalization of engineering and requires much greater interdisciplinary effort, interdepartmental collaboration, industrial interaction and teamwork. Further, since mechatronics is primarily a design strategy and since design activity is best carried out in heterogeneous teams working on a real industrial problem/project, a design-oriented curriculum can quite readily, as well as most suitably, fulfil these special requirements of mechatronics education. The objectives of the paper, therefore, are twofold:

1. To sum up the understanding of mechatronics as gathered from and operative in academic institutions and industrial environments worldwide into a new comprehensive definition of mechatronics.
2. To propose a model design-oriented curriculum based on this new definition of mechatronics.

The curriculum is aimed at developing mechatronics design specialists who would have the ability to retain constant awareness of the bigger picture of system level details, to prototype the whole design for the overall system and to effectively lead product development teams comprising specialists from various disciplines.

MECHATRONICS REDEFINED

Although any attempt to strictly and precisely define mechatronics would be contrary to its basic spirit, there are many situations where it does become necessary to have a reasonably concise, well-agreed and workable definition at hand [12]. As mechatronics is still in a continuously evolving and dynamic state [3], none of the so many existing definitions of mechatronics [1–3,10–18] can be said to be the best way to describe mechatronics. Therefore, for the purpose of developing a comprehensive proposal for an undergraduate educational program, an attempt has been made here to capture the intent of these previously formulated definitions of mechatronics in an exhaustive manner. Thus mechatronics is redefined here as follows:

> Mechatronics is a new strategic business paradigm of creative synergy that blends and cross-fertilizes precision mechanical engineering and electronic control as well as microprocessor, communication and information technologies within a concurrent engineering-based leadership framework for the design and development of smart products to ensure optimum, fast and precise performance, functional interaction and spatial integration using a unified flexible systems approach.

THE UNDERGRADUATE CURRICULUM

The model undergraduate curriculum as developed and described in the following paragraphs of the paper and as presented in Table 1 is based on the definition of mechatronics given above. Proposals similar to this model curriculum have been submitted in the authors' institution for starting fresh UG/PG programs in mechatronics. An attempt has been made here to synthesize various mechatronics programs being conducted all over the world and to develop a model UG curriculum suitable at a global as well as local levels. The model could also be utilized by other academic institutions as a generic core basis upon which a particular superstructure may be designed and built to suit specific local requirements, available expertise and facilities as well as to reflect institutional leanings and individual interests of faculty members involved.

The proposed curriculum envisions mechatronics as a new engineering design strategy, perceives it as a systemic business philosophy and emphasizes interdisciplinary communication, team effort and industrially relevant project-based learning. The curriculum lays emphasis on incorporating design more fully in the conventional contents of theory papers and attempts to teach integration of various areas covered under mechatronics through the design process particularly in the strong laboratory sessions. It is design-oriented rather than science- or analysis-based with all analysis problems/laboratory exercises being integrated as part of the design of a bigger system. Students are given ample opportunity to practice design through experiential hands-on activities in open-ended, industry-sponsored team design projects. The final group term project requires students to design a complete mechatronics system having industrial significance. The proposed curriculum thus integrates mechatronics as a design strategy throughout the entire program in a manner similar to the teaching of engineering design.

Teamwork is promoted through cooperative learning in small design groups comprising students from various disciplines/departments. Team performance also contributes significantly to individual's grades. The whole curriculum attempts to prepare the students to gain the ability to assume and transact strong leadership roles in exploiting the full business potential of mechatronics for the design of products in industrial settings.

THE COURSES

The importance of including traditional engineering subjects in mechatronics curriculum is well described in the references given against each subject in Table 1. The subjects M5.3 and M4.3 are taken to cover mechanical, electrical and electronic designs. Courses M4.1, M4.3 and M5.3 integrate modeling, mechanical design and electronic control as a crucial step in mechatronics education [4, 19]. Courses such as M2.2, M2.5, M4.3, M4.4, M5.3, M5.4, M5.6, M6.4, M6.5, M7.3

Table 1. The proposed design-oriented curriculum for mechatronics

1st Year—1st Semester	
Theory papers:	**Laboratories:**
M1.1 Mathematics I [10,20,21]	L1.1 Physics [23, 24]
M1.2 Physics [10, 20, 21]	L1.2 Chemistry
M1.3 Chemistry [20, 21]	L1.3 Computer Fundamentals(C++, etc.)
M1.4 Engineering Materials [20, 22]	L1.4 Communication Techniques and Skills [25]
M1.5 Computer Fundamentals [5, 8, 10, 20, 21]	
M1.6 Introduction to Mechanical Engineering [10]	
1st Year—2nd Semester	
M2.1 Mathematics II: (bond graphs [19], etc.)	L2.1 Solid Mechanics & Mechanisms
M2.2 Solid Mechanics/Strength of Materials [20]	L2.2 Electrical & Electronics [20]
M2.3 Fundamentals of Electrical and Electronics Engineering [6, 7, 26]	L2.3 Engineering Workshop (Electrical/Mechanical)
M2.4 Manufacturing Science and Engineering	L2.4 Machine (Electrical/Mechanical) Drawing and Engineering Graphics
M2.5 Mechanisms	
M2.6 Social Engineering/Engineering Economics	
2nd Year—3rd Semester	
M3.1 Engineering Thermodynamics and Heat Transfer [20]	L3.1 Thermal Engineering
M3.2 Fluid Mechanics and Machines	L3.2 Instrumentation and Measurement [4]
M3.3 Circuit Analysis [20]	L3.3 Microprocessor [4]
M3.4 Instrumentation and Measurement Systems [6]: (computer-based virtual instrumentation, etc.)	L3.4 Production Technology
M3.5 Microprocessors [7, 27, 28]	
M3.6 Production Technology	
2nd Year—4th Semester	
M4.1 Control System Engineering [7, 29, 30, 31]	L4.1 Control
M4.2 Sensors, Transducers and Actuators [1, 32, 33]	L4.2 Sensors and Actuators
M4.3 Design of Machine Components: (mechanical [26] and electrical)	L4.3 Mechatronics
M4.4 Machinery Dynamics and Vibration Analysis [20, 34]	L4.4 Dynamics of Machines [7]
M4.5 Digital Electronics [6, 34]	
M4.6 Introduction to Mechatronics	
3rd Year—5th Semester	
M5.1 Embedded Systems	L5.1 CAD
M5.2 Digital Signal Processing [34]	L5.2 Digital Electronics
M5.3 CAD [34]	L5.3 Product Design
M5.4 Design Optimization	L5.4 Creativity & Innovation/Motivation and Team work
M5.5 Human Factors and Applied Ergonomics [35]	
M5.6 Design Management	
3rd Year—6th Semester	
M6.1 CAM/CNC Technology/Computer Integrated Manufacturing Systems/Advanced Manufacturing Technologies	L6.1 CAM/CIMS
M6.2 Real time [36] and Parallel systems	L6.2 Real Time Systems
M6.3 Industrial Engineering	L6.3 Industrial Engineering
M6.4 Tribology	L6.4 FEA
M6.5 Finite Element Analysis [20]	
M6.6 Knowledge Engineering and Management/Data Base Management Systems	
4th Year—7th Semester	
M7.1 Business Management	L7.1 Robotics [7]
M7.2 Introduction to MEMS [20] and Nanotechnology	L7.2 MEMS & Nanotechnology
M7.3 Mechatronic System/Product Design	L7.3 Mechatronic System/Product Design
M7.4 Robotics and Automation [11, 37]	L7.4 Management & Leadership Development
M7.5 Concurrent Engineering Design [1]	
M7.6 Engineering Ethics and Leadership	
4th Year—8th Semester	
M8.1 Dissertation	
M8.2 Major Project & Seminar	

and M7.5 give the curriculum a strong design bias within a concurrent engineering framework. Manufacturing/ production/industrial engineering considerations are taken up in M2.4, M3.6, M6.1, M6.3 and M7.4. Courses M7.1 and M7.6 cover the business management, engineering ethics and leadership aspects. There are exclusive laboratories L1.4, L5.5 and L7.4 for the development of management skills and leadership capabilities as well as to enhance creativity and teamwork. Course M7.2 provides a futuristic orientation.

THE EQUIPMENT

Besides the usual equipment available in basic science laboratories, Table 2 provides a list of typical facilities required to support experiments

Table 2. List of equipment

S. No	Hardware	Software
1.	**Integrated CAD/CAM** (CAD workstations /PCs and server with accessories and peripherals such as UPS, plotter, printers, etc). CNC Turning Centre Trainer /CNC Lathe CNC Machining Centre Trainer/ CNC Milling (Suitable for production and training) Stratasys Stereolithography/Fused Deposition Modelling Machine for Rapid physical prototyping	Programming languages and operating systems for computer laboratory (C, C++, Windows NT, Unix, etc.) CAD/CAM/CAE, industrial design software Autodesk Mechanical Desktop/I-DEAS/ProEngineer/ SolidEdge/Unigraphics, ALIAS Software for CAD, CAE and FEA/mechanical event simulation (NASTRAN/ANSYS/PATRAN/Cosmos/Superdraw & Accupak/VE) Software for dynamic analysis and simulation (ADAMS) Software on the internet/surfing for virtual parts (Design suite)
2.	**General purpose mechanical and specific instrumentation for vibration modal analysis and testing** (Basic instruments, sensors, transducers, accelerometers and pickups, shakers, load cells, tachometer, strain gauges, photocells, potentiometers, manikins, microphones, modal hammer set, impact hammer set, instrumentation recorders, PC based dual channel FFT analyzer, PC based data acquisition and signal conditioning system, VXI plug and play library of modules, function generator/digital oscilloscope/multimeter/dynamometer, encoders, motors (servo, stepper, etc.) and other mechanical items/spares).	Platform for noise and vibration engineering (CADA-X). Control system analysis & design simulation software (For high-level simulation of complex systems. The combination of dSPACE and the worldwide de facto standard MATLAB®/SIMULINK® forms a complete solution for the development of mechatronic system. SigLab and MATLAB together form a powerful control system design tool.) Simulation driven design (MatLab/Simulink/VisSim/dSPACE/SigLab/PolyFEM/ DADS/DADS plant)
3.	**General purpose electrical/electronics instrumentation** (Microprocessor chips e.g., 68HC11, A/D & D/A converters, digital signal processors, MC68332 microcontroller, operational amplifiers, photo-transistors, discrete logic, timers and power transistors, signal conditioning circuits, electronic boards, ultrasonic detectors, infra-red emitter-detectors, LEDs, power converters, LCD display, LASER, limit switches, solenoid-operated gripper, anemometer, frequency to voltage converter, assorted analog/digital sensors, actuators and components , and electrical and electronics items/spares).	Viewing/navigation software/virtual prototyping and simulation software/automatic virtual environment/human factor analysis/suite of interactive products simulation software/virtual-world manikins (Studio, Studio Paint, and Composer/Hypershow/Stereoshow/Virtualshow/IVECS/ dVise, DVS/Vis Mockup DV/VR author, DV/Developer + DV/Runtime, DV/IGES, DV/Immersion, DV/I tools, and SDI Animater, etc./CAVE/Deneb ERGO/dV/Manikin/dV Immersion/VIVID/AutoCAD Designer/AutoSurf/3-D studio I/EMS/Model view)
4.	**Mechatronics, robotics and automation** LSM Controller, Automation training package SCARA robot system with real time multitasking controller RV pro machine vision system for robot guidance Linear slide base/X-Y table Motor kits, timing belts, encoders and other accessories to carry out industrial projects Mechatronics Power Pak Kit/Picstart plus mechatronics kit For mechatronics and control education and research/ Auto-Balancing, Flexible Shaft System & High Speed Magnetic Bearing Test Rig	Mechatronics software EMSS/Saber/Alaska/Microsim design lab (Pspice)/X-Win32/Electronics Workbench (SPICE-based).
5.	**Virtual instrumentation** Plug-in DAQ boards with GPIB, VXI, serial and industrial control interfaces, remote data acquisition, signal conditioning and instrument drivers. **Virtual reality system** (VR Engine computer/workstations/ BOOM/Crystal Eyes 3-D goggles/head mounted display (Liquid Image MRG 2.2. EyeGen3/V8)/data glove/Flock of birds (hand position sensor) 3Space Fastrak/Dual Rack Onyx2 Infinite Reality system/tracking systems)	Software for virtual instrumentation, industrial automation test and measurement device drivers, math, data analysis, visualization and numerical analysis and modeling. LabVIEW, LabWindows/CVI, MMI/SCADA software, Lookout & BridgeVIEW, Virtual –Bench and HiQ.
6.	**Coordinate measuring machine** (for precision measurements) and **testing machines and units** (Universal testing machine, hardness testing machine, impact testing machine, shock absorber field test unit, endurance test unit, etc.)	

in various engineering laboratories. The list has been compiled from scores of sources on the Internet, research papers, and advertisements in trade magazines and journals. Trademarked items can be easily searched on the World Wide Web. No references, therefore, have been cited for them to contain the length of the paper.

CONCLUDING REMARKS

Mechatronics is not just a new design strategy or technology, but also a new way of doing business to gain competitive advantage in the global marketplace. Mechatronics education has, therefore, come to receive significant attention worldwide and it will dominate the engineering education curricula in the foreseeable future. Since mechatronics is still undergoing a continuous process of dynamic evolution, the concept remains in an amorphous and heterogeneous state. As such, it is imperative for academic institutions to introduce equally quick changes in their curricula. The design-oriented model framework proposed here for mechatronics education can enable educators in identifying shortcomings in their present programs, in redefining their goals and objectives, in reformulating their priorities and in updating their curricula. However, the task of promoting mechatronics education requires much greater cooperation between governments, industrial organizations and academic institutions at a global level. In fact, it may be necessary to effect a massive restructuring at bureaucratic/organizational levels and to bring about a radical paradigm shift at psychological levels. Mechatronics is surely poised to represent a new emergent consciousness in engineering that would inspire creative design, nurture transformational leadership and enliven the spirit of cooperation in a fiercely competitive business scenario.

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