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Mechatronics and smart structures: emerging engineering disciplines for the third millennium

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Abstract

This paper tackles the impact that Mechatronics and Smart Structures disciplines have on the engineering education in the new millennium. Mechatronics is an emerging engineering area that will likely alter the fundamental nature of engineering education in the disciplines of electrical and mechanical engineering. It can provide an academic model for developing multi-disciplinary programs within the engineering college departmental structure that is historically based on the traditional engineering disciplines. Mechatronics integrates the classical fields of mechanical engineering, electrical engineering, computer engineering, and information technology to establish basic principles for a contemporary engineering design methodology. A mechatronics concentration area in the engineering curriculum would support the synergistic integration of precision mechanical engineering, electronics control, and systems thinking into the design of intelligent products and processes. Smart Structures, a. k. a. Adaptive Structures, a. k. a. Adaptronics, is an emerging engineering field with multiple defining paradigms. One definition is based upon a technology paradigm: "the integration of actuators, sensors, and controls with a material or structural component". Multi-functional elements form a complete regulator circuit resulting in a novel structure displaying reduced complexity, low weight, high functional density, as well as economic efficiency. Another definition is based upon a science paradigm in an attempt to capture the essence of biologically inspired materials by addressing the goal as creating material systems with intelligence and life-like features integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionality. Their basic characteristics of efficiency, functionality, precision, self-repair, and durability continue to fascinate designers of engineering structures today.

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1. Background

Mechatronics is an emerging engineering area that will likely alter the fundamental nature of engineering education, particularly (and initially) in the disciplines of electrical and mechanical engineering. The objectives of the program are: (a) to provide an academic environment for engineering undergraduates to acquire the multi-disciplinary knowledge and skills necessary to apply mechatronics in product design, development and manufacturing; and (b) to provide an academic model for developing multi-disciplinary programs within the engineering college departmental structure that is historically based on the traditional engineering disciplines. The Mechatronics area of concentration could offer engineering students a multi-disciplinary education in design and product development processes. It integrates the classical fields of mechanical engineering, electrical engineering, computer engineering, and information technology to establish basic principles for a contemporary engineering design methodology. In this methodology, engineering products and processes have moving parts that require manipulation and control of dynamic constructions to a required high degree of accuracy. Also, the design process requires enabling technologies such as sensors, actuators, software, optics, communications, electronics, structural mechanics and dynamics, and control engineering. A key factor for the design process involves integrating modern microelectronics and information technology into mechanical and electromechanical systems. Therefore, the mechatronics concentration area supports the synergistic integration of precision mechanical engineering, electronics control and systems thinking into the design of intelligent products and processes.

The discipline of *adaptive materials and smart structures*, recently coined as Adaptronics, is an emerging engineering field with multiple defining paradigms. However, two definitions are prevalent. The first definition is based upon a *technology paradigm*: "the integration of actuators, sensors, and controls with a material or structural component". Multi-functional elements form a complete regulator circuit resulting in a novel structure displaying reduced complexity, low weight, high functional density, as well as economic efficiency. This definition describes the components of an adaptive material system, but does not state a goal or objective of the system. The other definition is based upon a *science paradigm*, and attempts to capture the essence of biologically inspired materials by addressing the goal as creating material systems with intelligence and life features integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionality. It is important to note that the science paradigm does not define the type of materials to be utilized. It does not even state definitively that there are sensors, actuators, and controls, but instead describes a philosophy of design. Biological structural systems, for example, are the result of a continuous process of optimization taking place over millennia. Their basic characteristics of efficiency, functionality, precision, self-repair, and durability continue to fascinate designers of engineering structures today.

The emerging engineering fields of *mechatronics, adaptive materials, and smart structures* have captured the attention of many engineering professionals, academics

Table 1
Mechatronics courses at US universities (alphabetical listing)

University	Type	Course name and description/contact person
California Polytechnic State University [1]	Stream of undergraduate courses	Mechatronics Design Studio IME 101 – Introduction to Industrial and Manufacturing Engineering IME 356 – Manufacturing Automation IME 416 – Automation of Industrial System IME 455 – Manufacturing Design and Implementation-I IME 591 – Integrated Product Development I IME 592 – Integrated Product Development II Sema E. Alptekin, salpteki@polymail.calpoly.edu
Georgia Tech [2]	One undergraduate and two graduate courses	ME 4447 – Microprocessor Control of Manufacturing Systems ME 6403 – Digital Control Systems ME 6405 – Introduction to Mechatronics I. Charles Ume, charles.ume@me.gatech.edu
Idaho State University [3]	1 Course	ENGR g425 – Mechatronics D. Subbaram Naidu, naiduds@isu.edu
Iowa State University [4]	1 Course	ME 410 – Mechatronics Greg R. Luecke, grluecke@iastate.edu
Kettering University/ General Motors Institute [5]	3 Courses	ME 203, 204 – Introduction to Mechatronics Design ME 480 – Applied Mechatronics Jeffrey B. Hargrove, Mechatronics Laboratory, Jawa jhargrov@kettering.edu, Mariappan
Massachusetts Institute of Technology [6]	1 Introductory Course	2.737 – Mechatronics 6.270 – Autonomous Robot Design Competition Kamal Youcef-Toumi, youcef@mit.edu
Minnesota State University [7]	2 Courses, elective sequence	Mechatronics option for both ME and EE students C. Johnson, charles.johnson@mankato.msus.edu
North Carolina State University [7]	2 Introductory Courses	MAE 534 – Mechatronics Design M.K. Ramasubramanian, rammk@eos.ncsu.edu
Ohio State University [8]	2 or 3 Introductory Courses	ME 482 – System Dynamics and Electromechanics ME 674 – Introduction to Mechatronics 874 – Fault Diagnosis in Mechatronic Systems G 3 Giorgio Rizzoni, Rizzoni.1@osu.edu
Pennsylvania State University [9]	1 Course	Technical elective Mechatronics at senior level J.F. Gardner, jgardner@boisestate.edu
Purdue University [10]	1 Introductory Course	ME 597G – Mechatronics George T.-C. Chiu, gchiu@ecn.purdue.edu
Rensellaer Polytechnic Institute [11]	2 Courses	MEAE 4490 – Mechatronics MEAE 4250 – Mechatronics Systems Design, Kevin Craig, craigk@rpi.edu
San Jose State University [12]	1 Course	ME 106 – Fundamentals of Mechatronics B.J. Furman, http://www.engr.sjsu.edu/bjfurman/courses/ME106

discussing the possibility of starting a course to cover actuators available to mechatronic engineers. Stanford University also has an undergraduate course on Mechatronics. Its main focus is to provide sufficient information and background concerning the tools and technologies used by mechatronics engineers. In this way, the students can accomplish the task of solving a system design and integration activity as part of the course. Since the students are in the quarter system, this course only covers a 10-week span. Although similar to the format of the graduate sequence, the undergraduate laboratory exercises are done using pre-built frameworks to help the students get past some of the more tedious details that a project would call for, yet still allow the students to use what they learned and come up with a solution to a hands-on problem. Stanford acknowledges that mechatronics is too broad a topic to have a single course as a model for all mechatronics options.

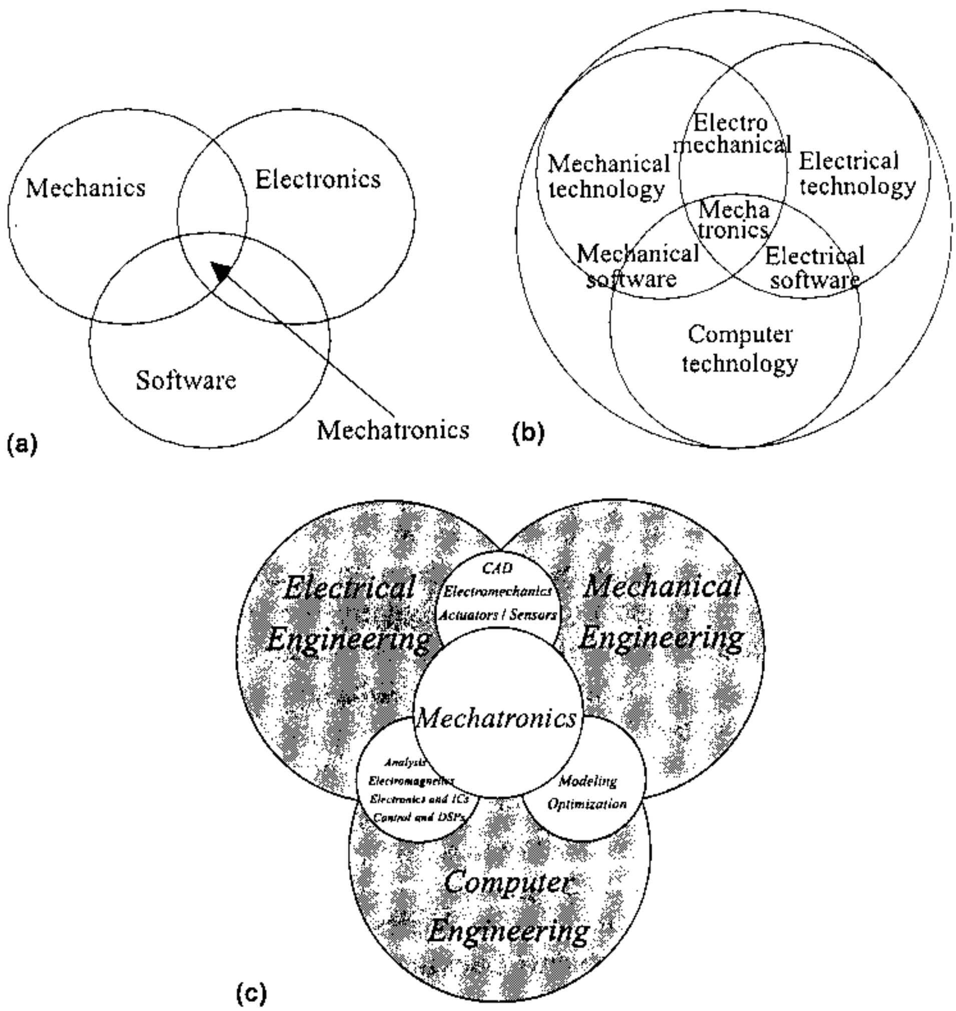

Fig. 1. Common diagrams used to illustrate how different disciplines combine to make up Mechatronics: (a) Stanford University concept [13]; (b) University of Missouri-Rolla concept [17]; (c) Purdue University concept [21].

2.2. University of Washington

In the 1996–1997 academic year, the University of Washington underwent a major change in its mechanical engineering undergraduate curriculum. This overhaul allowed students more freedom for specialization. Incorporated into this change was the addition of a mechatronics curriculum thread for the senior year. The thread was designed to attract 20 ME seniors from a typical graduating class of 170 students. This thread incorporated the existing embedded computing course with other existing mechatronics related courses (automatic control, instrumentation and design). The thread culminates in a final design course only available to the students who are completing the entire mechatronics thread. As with Stanford University, the students work in teams on open-ended design projects, with the goal of implementing a working prototype by the end of the ten-week course.

The educational objective of this mechatronics thread is to produce modern, work-ready graduates at the BS level who are well prepared for rewarding careers as designers of mechatronics products and processes. The success of this thread relies heavily on the curriculum leading up to it. The normal pre-requisites for the ME degree are required, but six of them are singled out as specifically pertinent to the

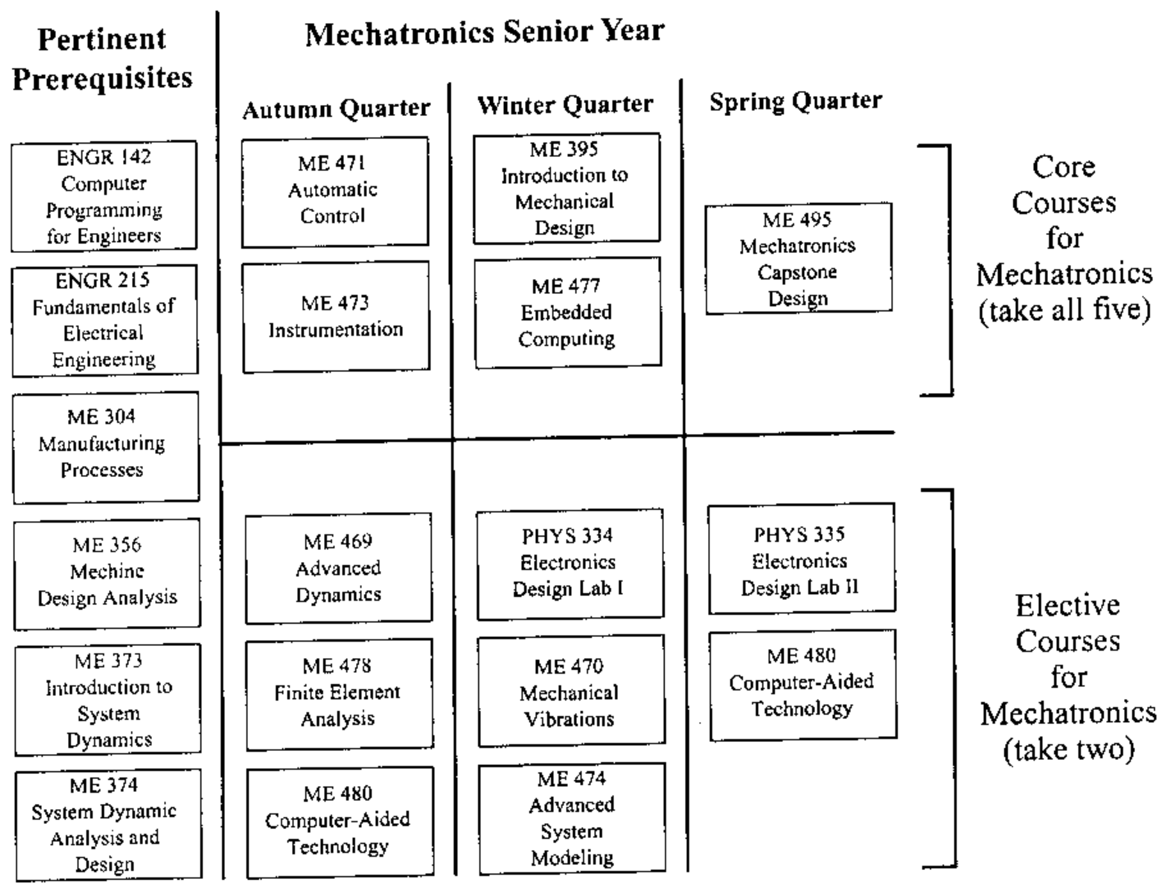

Fig. 2. Flow diagram of the Mechatronics thread at the University of Washington, Department of Mechanical Engineering [20].

mechatronics thread as shown in Fig. 2. A few examples of the working prototypes that have been created from the Mechatronics Capstone Design course in the past are: (1) a shaft dynamometer for a human powered submarine, (2) a scuba rate-of-ascent controller, an (3) a programmable oven Controller. The most important issue in teaching such a thread of courses, as pointed out by the University of Washington, is the careful selection of projects for the design course. The professor(s) must match a project to the students' capabilities as learned from the previous courses. It is important to choose projects that are challenging to the students, but ones with goals that are realistically attainable during short term of the class.

3. Mechatronics and smart structures education at University of South Carolina

3.1. Situations today

At present, University of South Carolina (USC) College of Engineering does not have a Mechatronics education stream per se. There are a number of separate courses in Mechanical and Electrical Engineering Departments that could make the foundation of a Mechatronics education, but they are not yet assembled into a coherent stream. The Department of Mechanical Engineering has a number of courses that interweave mechanical/electrical/electronics concepts, as detailed below. In addition, the Department of Mechanical Engineering has recently organized the *Laboratory for Active Materials, Smart Structures, and Mechatronics* to study the multi-facet applications of these technologies.

The courses that exist in the Mechanical Engineering curriculum and will be included in the Mechatronics concentration area are EMCH 260 – Introduction to the Mechanics of Solids; EMCH 371 – Engineering Materials; EECE 221 – Circuits I (taught by Electrical Engineering Department); EMCH 361 – Measurements and Instrumentation; EMCH 367 – Fundamentals of Microcontrollers; EMCH 467 – Mechanical Engineering Laboratory; EMCH 427/428 – Mechanical Design I/II; EMCH 377 – Manufacturing Processes (including electronics fabrication); EMCH 585 – Nature of Composite Materials; EMCH 509 – Computer Aided Manufacturing; EMCH 521 – Concurrent Engineering; EMCH 561 – Design for Manufacturing and Assembly; EMCH 575 – Adaptive Material Systems and Structures.

3.2. Development of the ECH 367 course – fundamentals of microcontrollers

The current curriculum covered in the EMCH 367 course is multi-disciplinary and constitutes important knowledge for our graduating mechanical engineers. However, with the amount of material that quickly becomes "related topics" when teaching this course, one could quickly overwhelm the student with too much information and end up with a frustrated student who is trying to "survive" this course. Apparently, this was the case several semesters ago. Since then, changes have gradually been implemented to eliminate some of the more sophisticated topics and focus on getting the major Mechatronics concepts across to the Mechanical Engineering students. A major effort has also been invested into updating the programming-language environment and making the process more palatable to Mechanical Engineering students. This has made the course more true to its name, "Fundamentals of Microcontrollers". As discussed previously in this paper, the need exists to develop further instructions in this area. Ideally, just as some of the other universities have done, the ultimate goal would be to have a stream of classes that would allow a student with an interest in the Mechatronics area to take advanced courses that would provide the knowledge and hands-on experiences that they need and desire.

3.3. Other plans within the USC College of Engineering and Information Technology

The Department of Mechanical Engineering at the USC College of Engineering and Information Technology has taken upon itself to lead a Mechatronics education initiative that will rally together the resources of the departments of Mechanical Engineering (ME), Electrical Engineering (EE), and Computer Science and Engineering (CSE). This initiative is consistent with the blending together of the undergraduate education, graduate education, and research into a smooth continuum. The vision that is embraced is that, starting with the fourth (senior) year of undergraduate educations, the Mechanical Engineering students will enter a tracks system and will be able to choose their courses in order to realize the goals and objectives of their particular area of emphasis. The planned areas of emphasis in Mechanical Engineering include (but not limited to): Mechanics of Materials, Energy Systems, Manufacturing/Design, and Mechatronics. Of these tracks, Mechatronics offers the widest opportunity for interdisciplinary/pluridisciplinary specialization. This will manifest in both the electives available under the Mechatronics track, and in the way they are to be selected. We view Mechatronics in a wide sense, to cover controls, automation, intelligent manufacturing, smart structures, and artificial intelligence. Hence, the elective offerings will be not only from the department of Mechanical Engineering but also from the Department of Electrical Engineering and from the Department of Computer Science and Engineering. Some of these areas are common with the other departments, e.g., Electrical Engineering (EE) or Computer Science and Engineering (CSE). However, we view the EE approach more like a process focus on the details of the electrical/electronics components and the control of the electrical system, while the ME approach is focused more on the complete product, covers the electro-mechanical-information systems, and how the parts work together and perform effectively. Regarding the way electives are selected, let us illustrate with an example. For an area of emphasis within the regular Mechanical Engineering specialty, an ME senior year student may have to choose three electives from the track, and one elective from outside. However, for the Mechatronics track, with its highly interdisciplinary/pluridisciplinary flavor, out of the four electives two will come from Mechanical Engineering offerings, and the other two may come from either Electrical Engineering or Computer Science and Engineering or from both.

At graduate education level, the same multi-disciplinary/pluridisciplinary approach to Mechatronics will be taken. For an ME Master of Science (MS) student specializing in Mechatronics, the MS committee will ensure that the courses taken and the research area cover cross-boundary interdisciplinary aspects that come together with the EE and/or CSE departments. For the Ph.D. student, the Ph.D. committee will draw faculty not only from ME department but also from EE and/or CSE departments. The interdisciplinary/pluridisciplinary aspects will be embodied in the course selection guidelines for these students.

One example of a integrated Mechatronics approach is the Camless Engine research project. In this project, we consider using commercially off the shell (COTS) sensors and signal conditioners to send a signal to the control unit that will activate a fast-response induced-strain/hydraulic actuator that will effect the mechanical motion needed to produce the engine valve opening at the precise required time. Another example is the machinery health monitoring project in which an array of specific sensors placed on vital machinery parts that are constantly subjected to vibratory operational loads will capture the state of structural and operational health of this machinery and send the data to a distributed digital signal processor network. Based on the recorded data and on a historical database of possible signal signatures connected with possible machine conditions, an artificial intelligence controller using expert systems and Bayesian networks will make the correct machinery diagnostics and issue an operational prognosis. This operational prognosis will allow the operator of the sensitive vital machinery to choose the appropriate course of action that will permit performance of most of the missions in the safest and most cost-effective manner.

The long-term education objective of Mechatronics instruction is to develop in our students the right blend of technical knowledge, scientific tools, and communication skills. This process parallels the manufacturing paradigm of simultaneous quality/cost/time optimization (Fig. 3). In this way, they will be optimally prepared

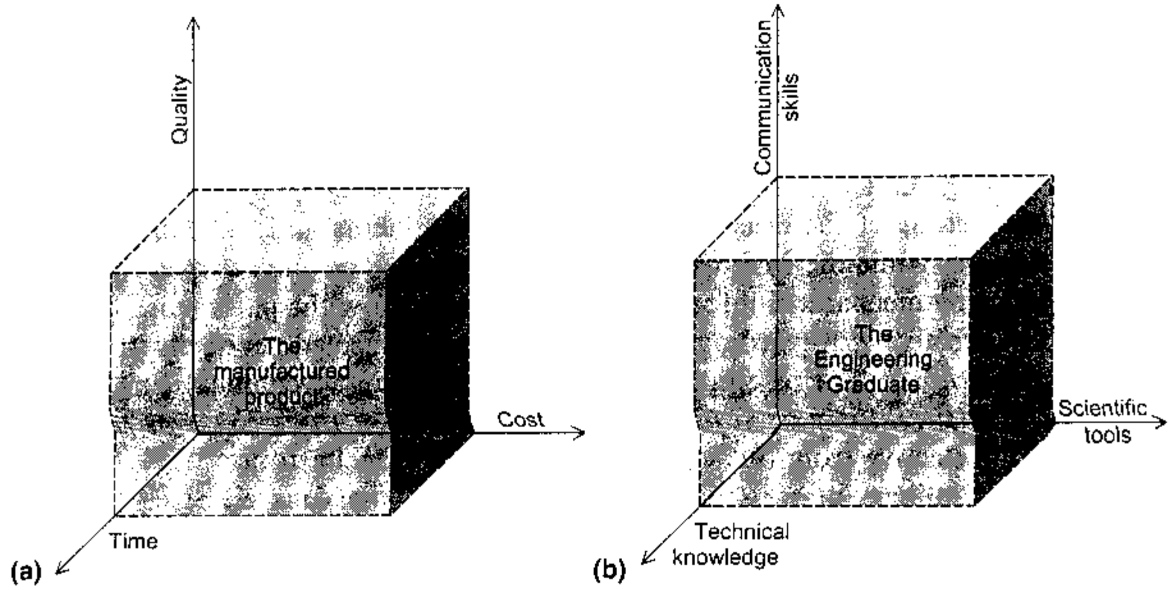

Fig. 3. Comparison of manufacturing and educational multi-dimensional production optimization paradigms: (a) the quality/time/cost manufacturing model; (b) the technical knowledge/scientific tools/communication skills educational model.

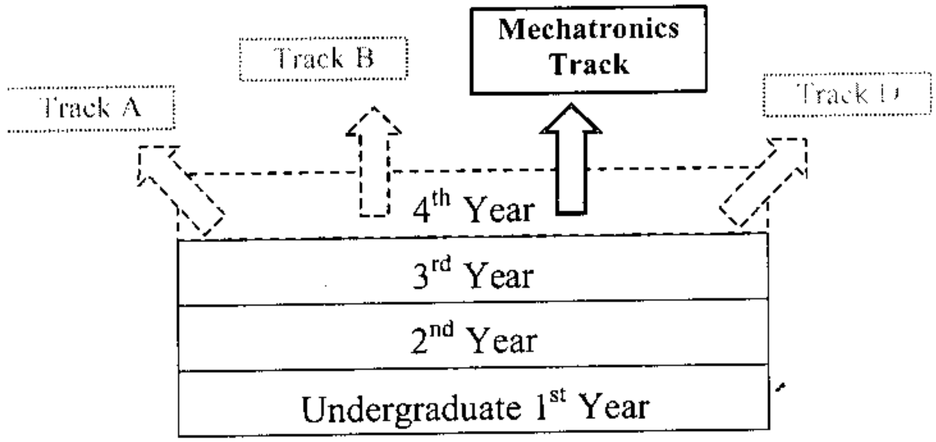

Fig. 4. Conceptual diagram of the Mechatronics track insertion into the USC-Mechanical Engineering curriculum planning.

to meet the design/analysis/manufacturing challenges that their future employers will pose on them. Today's and tomorrow's products are a intertwined blend of mechanisms, sensors, actuators, electronics, and information technology. The ideal graduate should be able to hit the ground running in all these areas concurrently in order to achieve maximum performance with minimum training/adaptation time. This will ensure that the quality/time/cost requirements are simultaneously met in the most effective way. Of course, the "ideal graduate" is not a physical reality, but a graduate with a broad Mechatronics education will come pretty close to it.

A proposal to establish a track (concentration) system within the undergraduate programs in Mechanical Engineering is under consideration by the Undergraduate and Graduate Studies Committees in both Mechanical and Electrical Engineering Departments. The track system will be very similar to that of the University of Washington, and will cover several tracks, one of which is Mechatronics, as shown in Fig. 4. The courses will be covered by the two departments (Mechanical and Electrical). Four courses will be coming from a list called "Mechatronics List" and two more electives will be coming from other track lists such as Control and Dynamics, Design and Manufacturing, Mechanics and Materials, Energy Systems, etc.

4. Conclusions

Many universities have started offering courses on Mechatronics to undergraduate and graduate students. Such courses, cutting across departmental boundaries and combining theory, hands-on experiments, and technology applications, greatly benefit the undergraduate students, graduate students, and even faculty. They propel the curriculum towards the forefront of engineering education and directly answer the training and education challenges of the 3rd millennium. At the USC, the Department of Mechanical Engineering is fully engaged in establishing new graduate and undergraduate courses, and graduate research programs, in the areas of adaptive material systems and structures, and mechatronics. This shows that USC has already embarked on smart materials technology and mechatronics education and research. Smart-materials-based health monitoring techniques utilizing miniaturized active sensors are being developed for automotive, aerospace and civil engineering applications. Adaptive materials actuator solutions are being studied for a variety of applications ranging from aerospace through automotive applications. Mechatronics education efforts are being pursued internally, in the Department of Mechanical Engineering, and externally, within the College of Engineering and Information Technology, in cooperation with the Department of Electrical Engineering and the Department of Computer Science and Engineering.

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