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Effective Integration of Mechatronics into the Mechanical Engineering Curriculum: A Cooperative, Project-Based Learning Model with Seamless Lab/Lecture Implementation*

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In today's competitive markets, engineers face ongoing challenges to produce complex engineering systems with a high level of performance, reliability, value and price. This requires the integration of a number of technologies, which may be accomplished through mechatronics. This paper presents a model for integrating mechatronics education into the Mechanical Engineering curriculum at the American University of Beirut (AUB). A strong component of the model is collaborative, project-based, learning-by-doing experience in which students realize mechatronics devices, possibly of their own choosing, using various laboratory tools including microcontroller technologies. The implementation strategy involves minimal lecturing, a seamless lab/lecture interface, and just-in-time learning. An example of a typical student's project is presented and course assessment is briefly discussed.

INTRODUCTION: WHY IS MECHATRONICS IMPORTANT?

THE BREATHTAKING SPEED at which technology is advancing is influencing to a large extent the future and spirit of the world in which we live. 'Properly harnessed and liberally distributed, technology has the power to erase not just geographical borders but also human ones' [1]. Economies are becoming more dependent on knowledge and technology than on natural resources. As microprocessor technologies continue to advance, becoming small, cheap, and more powerful, successful products of yesterday fade in comparison with tomorrow's possibilities. Competing in a highly competitive global market requires the commercialization of knowledge and technology to produce better, faster, cheaper, multi-functional, flexible, and intelligent products. To this end, engineers involved in the product realization process must master technology as it develops and quickly integrate it into products well ahead of the competition. Mechatronics, being an interdisciplinary engineering field, plays a key role in achieving this goal [2, 3]. The importance of mechatronics is manifested by the myriad of smart products that we take for granted in our daily lives, from the little robotic toy that can climb walls to all the stuff that constitutes a modern 'electronic vehicle': engine controls, anti-lock braking systems, active suspension systems, collision avoidance, drive by wire, electronic muffler, and all the functionality of a PC residing beneath the dashboard [4].

Mechatronics' aim is to integrate various technologies, including electronics, mechanical devices, real-time control, microprocessor, materials, and human-computer interaction, from the very earliest stages of the conceptual design process and throughout the embodiment phases of the design process to introduce to the market simpler, smarter, higher quality, and more competitive products in a shorter time [5]. While many social, economic, and political forces are ultimately responsible for producing the necessary technical drive, education plays a vital role in preparing engineers who are capable of developing products that suit the spirit of the times. The contribution of the curriculum in this process represents a link in a chain that must be strengthened.

The importance of mechatronics education prompted the Editorial Board of the International

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Journal of Engineering Education (IJEE) to dedicate a special issue on the latest ideas in mechatronics education [6]. The issue included many articles which outlined mechatronics programs at both the undergraduate [7–11] and graduate levels [12] at various institutions. Djordjevich and Venuvinod [13] presented a case to integrate electronics and control courses to form a mechatronics program that enable manufacturing engineers to become technology integrators at the machine, work center, or shop-floor level. Xu and Bright [14] outlined the PKBot intelligent robot project that simulates lawn mowing operation. Grimheden and Hanson [15] investigated the potential benefits of international collaborative learning in mechatronics. Carryer [16] described the approach used in introducing embedded programming to mechanical engineering students in the mechatronics introductory courses at Stanford University. Petric and Situm [17] described a mechatronics course in which students learn through projects. The authors presented a pneumatically-driven inverted pendulum as one of the laboratory projects used in the course. The Mechatronics Education issue of the IJEE also included several articles describing specific experiments for mechatronics laboratory experiments, including thermal time constant experiment [18], PID and fuzzy control experiment [19], and a low-cost system to teach condition monitoring [20].

MECHATRONICS ENGINEERS

A mechatronics engineer is one who views a system as a whole and offers an optimum solution to a multivariable problem. To perform correctly, contemporary systems and products rely on harmonious interaction between mechanical systems, sensors, actuators, and computers. Thus, to realize multi-functional, flexible, smart, and precise machines, a mechatronics engineer must be able to transcend barriers that existed in the past between the various engineering disciplines. Realizing a mechatronics system in its most sophisticated form requires expertise in:

- selection, design, and implementation of the mechanical components;
- selection and implementation of sensors;
- design and implementation of interface circuitry;
- selection and implementation of appropriate actuators;
- mathematical modeling of the process involved;
- design and implementation of the controller; and
- use of microprocessor software and hardware development systems.

These many facets underline the essential ingredients required to develop a mechatronic system and the importance of team effort by the specialists in its realization. However, a mechatronics engineer generalist can acquire the skills needed to envision, design, and build mechatronic devices.

This article presents a model used in the Mechanical Engineering Department at AUB to educate mechanical engineers to become mechatronics generalists. The various elements of the model are not necessarily new [21–26], but the way they are integrated is believed to be. The model also satisfies many of the educational outcomes stated in the ABET EC2000 criterion 3 [27].

MECHATRONICS EDUCATION AT AUB: GOALS AND OBJECTIVES

Traditionally, ME students are trained to design mechanical systems for motion, strength, and other criteria, but they receive little or no training on how to interface a mechanically functioning device with its surrounding environment using the appropriate sensors, actuators and controllers. To address this deficiency, ME students should be provided with the proper environment to integrate electrical, digital and mechanical systems to develop embedded mechatronic devices. There is a universal agreement that this is best accomplished through collaborative, project-based, hands-on training [21–26]. Therefore, the goal is to enhance the ME curriculum to produce graduates who are able to:

- integrate diverse engineering knowledge in order to create efficient solutions to pressing current and future technical problems;
- achieve the ability to work successfully in multidisciplinary teams;
- apply creativity to design, develop and evaluate alternative solutions to real-world problems;
- obtain a holistic understanding of the product design and development cycle;
- learn the basic skills of leadership; and
- become self-motivated and lifelong learners.

Based on these goals, specific objectives that are congruent with ABET EC2000 criterion 3 are identified that define the circumstances that will demonstrate the desired effect on students and student learning. These objectives are:

- Students will learn how to obtain and integrate knowledge from various engineering disciplines to achieve a successful solution to complex technical problems.
- Students will learn how to break down a complex problem into manageable components, how to efficiently assign roles within a team, and how to interact with each other to achieve the desired goals.
- Students will demonstrate the ability to obtain and apply basic engineering skills that have traditionally been outside their major discipline to meet the needs of specific projects.

- Students, confronted with an open-ended problem, will be able to generate a number of diverse solutions that exhibit creative thinking, beyond classroom examples.
- Students will be able to demonstrate the planning of the entire development cycle of a specific product, from the statement of need up to a functional product.
- Students will develop skills in effectively organizing the processes of the group and play different roles within the team, especially a leadership role.

INFRASTRUCTURE IN SUPPORT OF OBJECTIVES

In an effort to achieve the aforementioned goals and objectives, the ME curriculum at the AUB has begun to respond to the need of its graduates to have mechatronics experience, through the establishment of a Mechatronics and Intelligent Machines Laboratory (MIML) and the introduction of two courses, Mechatronics and Intelligent Machines Engineering (MIME) I and II. The focus in the MIME-I is on embedded systems in which the microcontroller technology is introduced as an element of the complete system with an emphasis on hardware and software required to interface the microcontroller with sensors, actuators, and mechanical components. This course has been taught four times since its inception in the spring of 2000. Although the course is very demanding, it is well received by students and the demand for the course always exceeds the enrollment limit dictated by the limited number of available lab stations. MIME-II is a graduate course, which has been introduced to further enhance students' mechatronics experience. The focis in this paper will be on MIME-I.

The MIML laboratory creates an environment where students' technical and nontechnical skills can be nurtured through the design and development of open-ended projects using a hands-on approach. While it continues to evolve, the MIML currently consists of five complete laboratory stations. Each laboratory station consists of the following items: a Motorola 68HC11 microcontroller evaluation board (EVBU), actuator and sensor kits, power supplies for the EVB board and target system application, oscilloscope, function generator, multi-meter, a project development board, and an internet-connected PC equipped with a high-speed data acquisition board. The following supporting software programs are available on each PC: a 68HC11 C-compiler, assembler, and simulator from IAR systems, PSPICE for simulating electric circuits, Circuit Maker to model and prototype designs, and Matlab, Simulink and Control tool box from Mathworks for simulation and control activities. While the software programs are not all used by all teams in all projects, they are made available in support of projects when needed. Additionally, some of the programs are acquired to support the MIME-II course. The laboratory is also equipped with a Motorola Modular Development System M68MMDS11 and support components to provide a sophisticated platform for embedded system development using the 68HC11 and 68HC12 Motorola microcontrollers. The MMDS11 is only used in special projects and in final-year projects that could not be handled by the EVBU. The MIML also includes a bookshelf of manufacturers' handbooks and manuals, reference books, and related magazines, and cabinets of various analog and digital components, stepper motors, DC motors, servos, motor driver ICs, transistors, IR emitter/detectors, solenoids, cables, sensors and accessories.

IMPLEMENTATION STRATEGY

Students are grouped in teams of four from day one of the course. Each team is assigned a laboratory station and a project work area, which are used for building simple experiments, practising lecture content and developing assigned projects. The strategy for implementing the desired course/lab educational outcomes and objectives is summarized in the following sections.

Lecture/laboratory environment

The approach taken deviates from the conventional separation between lecture and laboratory components. In this new approach, lectures and lab experience are completely integrated. To provide students with the incentive and opportunity to take more responsibility for their learning, lecturing in the course/lab period is kept to a minimum. In a typical class/lab session, the instructor introduces major features of a given topic for a short portion of the class period. The instructor then plays a facilitator's role for the rest of the period. As students work on their projects, questions always come up that require *just-in-time learning*, which is managed in a manner that enables students to obtain answers on their own. Additionally, students are free to roam around the lab, ask each other questions and learn from each other's experiences. In many class periods, the instructor serves as a source of information and overseas activities to ensure student teams engage in effective cooperative, learning-by-doing effort to practice what they learn in the lecture.

Collaborative project-based learning

The course/lab focuses on open-ended projects instead of on a sequence of structured laboratory experiments. Students in a given semester are required to complete four or five meaningful projects, depending on the complexity of the projects. In each project, students are required to develop an application-specific mechatronic device. While the instructor suggests a project statement, teams are given the opportunity to provide a project statement of their own. If the student-generated idea for a project is comparable in scope with that suggested by the instructor, then the team is allowed to pursue that idea. The aim of student-generated ideas is to involve students in deciding what they want to learn and get them to work on something they may further pursue after graduation, thereby enhancing their entrepreneurial prospects. It is also designed to reflect the role of engineers as problem definers, in addition to being problem solvers. Teams who choose to work on an instructor-suggested project are also encouraged to modify the project statement and add to it features they deem important and relevant to their current or future needs. The projects assigned during the fall semester of 2002 were: a home security system, a smart elevator, a mobile robot, and a conveyor belt system. At the end of each project, each team is required to make a presentation on the device in the presence of the other teams' members and to provide a detailed formal report. Although the projects comprise the main assignments in the course, lab quizzes to implement freshly presented topics, two exams, and additional homework are also required.

CASE STUDY OF A TEAM PROJECT: SMART ELEVATOR

An example of an instructor-assigned project, further modified by students, was to design and build a three-story small-scale elevator that is activated either by the sound of a human voice or in the normal way by pressing the desired floor keys. The elevator (Neovator) also has to be user-friendly for disabled people.

Figure 1 shows the main components of the elevator. The elevator is controlled via a PC to which a 68HC11 microcontroller is interfaced. The project integrates the use of many programming languages, C++, Visual Basic, and assembly with the voice recognition software, Voice Xpress. While class lectures focused on assembly and the 68HC11, students used other language skills learned in a course on programming, and languages they learned on their own to complete the system. Additionally, no formal lectures on interfacing the 68HC11 with the PC were given. Students learned and implemented this skill on their own. Self-learning and research are essential attributes of engineers, as the EC2000 criterion 3 states. The project also provided students with the opportunity to use the programmable timer, interrupts, A/D converter, and I/O ports facilities on the 68HC11, displays, and interface electronics (analog and digital). The temperature—measured by a thermistor—is displayed on a screen via voice command. Mechanical design skills acquired in earlier ME courses were also utilized to design and implement elevator guides for the car, bearings, hoisting, gear-drive, housing, etc.

The PC is the master brain that controls the operation of the Neovator. Once a voice command is received, the voice recognition software, Voice Xpress, runs two executable files. The first '.exe' file, coded in C++, generates the appropriate signal to the PC serial port. For example, if the PC receives the command 'Go to Floor 1', it writes '&h2' to address &h379, which sets the 10th pin of the PC parallel port to 1. This in turn commands the 68HC11 microcontroller to send the elevator to floor 1. Similarly, a command 'Go to Floor 2' or 'Go to Floor 3' would cause the PC to write '&h4' and '&h8' to address &h379 and set the 11th and 12th pins on the parallel port, sending the elevator to floors 2 and 3, respectively (&h for hexadecimal in C++). The second '.exe' file, coded in Visual Basic, displays the floor number on the PC screen. Once the elevator reaches a floor, the door opens automatically, allowing the passenger to go in or out.

The floor-selection keys are interfaced to pins PC0–PC2 of the 68HC11 port C. When the elevator passes a given floor, it trips a corresponding switch so that, when the desired floor switch is closed, the software knows that the car has reached the destination floor. The floor switches are interfaced to port C pins PC3–PC5. The ON/OFF and direction of motion of the drive motor are supplied via pins PC6 and PC7 of port C.

The code operates as follows. The CPU scans

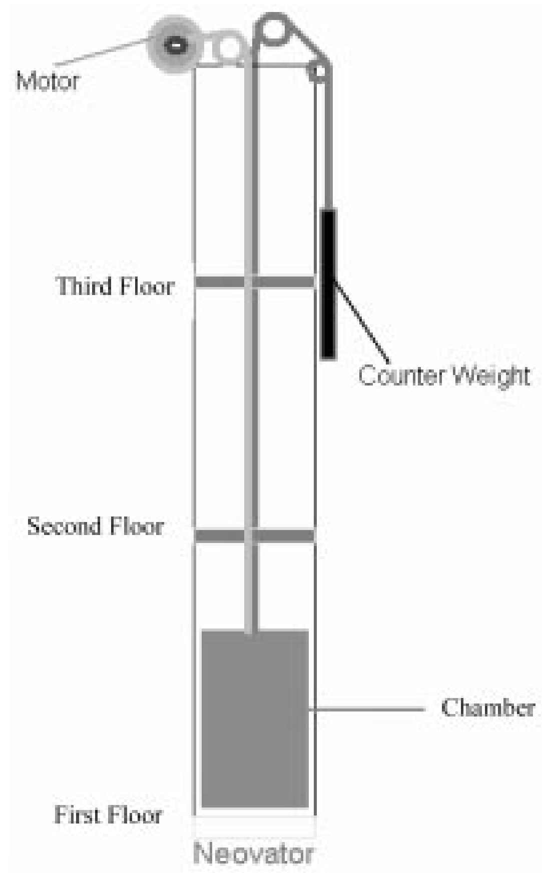

Fig. 1. Schematic of the elevator system.

Port C until a high at a pin to which a floor key is interfaced is detected. It compares the input to a ram variable that keeps the current location of the elevator. The result of this comparison is used to define the direction of elevator travel, either up or down. The elevator starts to move in the proper direction until the destination floor-switch is closed, signaling the arrival of the elevator at the desired floor.

The thermistor that is used as a temperature sensor is interfaced with the A/D converter via pin PE1 of port E of the 68HC11. The thermistor signal is filtered, amplified, and then subtracted from an offset so that the output falls within the full scale of the A/D converter, which is 0 to 5 V. The A/D converter is scanned continuously and the result is written to port B, where it is retrieved by the PC and displayed on a terminal screen whenever the Voice Xpress recognizes the 'READ TEMPERATURE' command.

ASSESSMENT

Assessment of the mechatronics experience at AUB is encouraging. Students who had taken the course for the previous three years (54 students) were polled by asking them several questions on various aspects of the course. The questions asked and the number of students selecting any of the optional answers were as follows.

1. Overall experience you had in the course:
   Excellent (34), Good (18), Average (1), Marginal (0), Terrible (0); No answer (1)
2. The cooperative learning approach is ideal for this course:
   Strongly agree (33); Agree (21); Disagree (0)
3. A good balance was maintained between self-learning and what should be learned by lecturing:
   Strongly agree (11); Agree (31); Marginally Agree (10); Disagree (2); No answer (1)
4. The team project approach to learning the material is:
   Excellent (36); Good (15); Average (2); Marginal (0); Terrible (0); No answer (1)
5. Would you suggest having more homework assignments and less lab projects?
   More homework/Less projects (17); Less homework/More projects (19); All homework (0); All projects (15); Remain the same (3)
6. Assess the knowledge acquired in this course in the context of your ability to integrate this knowledge with other forms of knowledge acquired in other courses:
   Excellent (21); Good (28); Average (5): Marginal (0); Terrible (0)
7. Do you feel more confident in your abilities as an engineer in a technical world having learned about the microprocessor interface than you would if you had not learned such technology?
   Yes (50); No (1); Not sure (3)
8. Would you recommend this course to your peers?
   Yes (45); No (5); Not sure (4)

It is clear from these responses that the students' overall experience in the course was positive, and that the collaborative, team-project approach is ideal. As far as the mix of homework and projects goes, students seem to like all the project options, although some would prefer more homework than was assigned. Overwhelmingly, students felt more confident in their abilities as engineers in a technical world having learned about the microcontroller interface and would overwhelmingly recommend the course to friends.

In addition to the above questions, students were asked to write general comments about their overall experience and to suggest improvements. Most comments centered on two concerns: 1) the workload in the course was overwhelming and 2) the laboratory equipment and physical environment need improvement. As both concerns are being proactively addressed, the course and lab experience is bound to improve.

SUMMARY

This article has presented a model to provide mechanical engineering students at the American University of Beirut with the necessary skills to develop mechatronic devices. Such skills are required of mechanical engineers in order that they can operate in a work environment in which the barriers between the various engineering disciplines continue to shrink into oblivion, and integration of mechanical systems with sensors, actuators, computer interface and control is becoming increasingly important for realizing smarter and better products. Additionally, a mechanical engineer with mechatronics skills is more likely to engage in an entrepreneurial venture, as he/she is more capable at looking at the 'whole picture'. The paper describes an educational model for achieving the desired outcomes. A strong component of the model is that it operates as a collaborative, hands-on experience in which students construct mechatronics devices, possibly of their own choosing, using various laboratory tools including microcontroller technologies. The model also encourages the students to take most of the responsibility for their learning, which is an important attribute of a contemporary engineer.

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