A 10-Year Mechatronics Curriculum Development Initiative: Relevance, Content, and Results—Part II

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Abstract—This paper describes the second and third phases of a comprehensive mechatronics curriculum development effort. They encompass the development of two advanced mechatronics courses (“Simulation and Modeling of Mechatronic Systems” and “Sensors and Actuators for Mechatronic Systems”), the formulation of a Mechatronics concentration, and outreach research activities in the mechatronics area. The first phase involved the design of an “Introduction to Mechatronics” course and the infusion of mechatronic activities throughout the curriculum and in outreach activities and has been described in a companion paper “A 10-Year Mechatronics Curriculum Development Initiative: Relevance, Content, and Results—Part I” (IEEE TRANSACTIONS ON EDUCATION, vol. 53, no. 2, May 2010).

Index Terms—Curriculum development, mechatronics education, project-based learning, sensors, system modeling.

I. INTRODUCTION

MECHATRONICS is a term that refers to the knowledge area encompassing the traditionally separate disciplines of mechanical and electrical engineering (ME and EE, respectively). Specifically, it is an interdisciplinary field that caters to the needs of a growing number of commercial products and industrial processes that involve the integrated use of mechanical and electronic components as well as control software in their design and development. While electromechanical systems predate the emergence of the term “mechatronics” about 40 years ago, its use is intended to emphasize that mechatronic systems can be optimally designed only when they are conceptualized in a concurrent manner by engineers educated in all of the constituent knowledge areas.

An interesting discussion as to which brand of engineer should lead the mechatronics design team as well as examples that illustrate the integrated nature of the area is found in [1]. Setting aside the issue of leadership, it is evident that there is a pressing need for engineers with skills in the mechatronics area who also have the ability to communicate well and work in interdisciplinary teams.

The authors have been part of a long-term effort at the University of Detroit Mercy (UDM), Detroit, MI, to address the above need, and the first phase of the initiative has been described in [2]. That phase involved the introduction of mechatronics activities across the undergraduate curriculum as well as in precollege outreach programs. The centerpiece was the creation of an upper-level undergraduate “Introduction to Mechatronics” course that provided students with an opportunity to experience a hands-on, team-oriented, project-based course with team members from another discipline.

The very first offering of the introductory mechatronics course included dedicated, but limited, modules on the topics of sensors and actuators as well as simulation and modeling of mechatronic systems. However, in assessment conducted at the end of the course, it was pointed out by students that the modules, while interesting in themselves, did not quite fit in with the main aim of the course, namely a team- and project-based introduction to mechatronics centering on the design and construction of a small autonomous vehicle. In essence, students were saying that the additional knowledge was not something that they could use in implementing their project and was, consequently, a distraction. Simultaneously, it was deemed that separate courses dedicated to sensors and actuators and the modeling and simulation of mechatronic systems would be needed to provide comprehensive treatment of the various components of a mechatronics system.

The advanced-level courses developed—“Simulation and Modeling of Mechatronic Systems” and “Sensors and Actuators for Mechatronic Systems”—are described in Sections II and III of this work. Section IV discusses course assessment and contains feedback provided by students who took the two advanced courses. This work, along with that described in [2], paved the way for the third phase of the effort, which involved the formulation of a mechatronics concentration or minor at the graduate level; this third phase, along with a description of research activities spawned by the authors’ involvement with the mechatronics area, is presented in Section V. Section VI concludes the paper.

II. MODELING AND SIMULATION OF MECHATRONIC SYSTEMS

“Modeling and Simulation of Mechatronic Systems” is designed to be a technical elective for both mechanical and electrical engineering senior undergraduate students as well as graduate students. The course has been offered four times so far (2008) and is scheduled to be offered annually. A summary of the course is provided here, and assessment results are discussed in Section IV. More details can be found in [3] and [4].

A. Learning Outcomes

The course learning outcomes are the following:

1) understand how to implement a structured approach to model mechatronic systems (systems consisting of mixed physical domains);
2) learn to develop the governing mathematical equations from the model of the mechatronic system;
3) be able to simulate system dynamic behavior for different input conditions;
4) be able to interpret simulation results to determine system behavior in physically meaningful terms;
5) gain proficiency in the use of appropriate software tools;
6) be able to work collaboratively across disciplines and cultures on mechatronics simulation projects;
7) demonstrate effective oral and written communication skills in the context of collaborative exercises on mechatronics modeling and simulation.

B. Course Content

The modeling tools used in this course are known as bond graphs. A bond graph [5] is a graphical representation of power flow through a system, a concept developed by Prof. H. M. Paynter in 1959 to enable modeling systems in terms of power bonds. In this approach, a system is represented as a network structure made of a few basic elements such as resistance, capacitance, inductance, and so on that are interconnected in an energy-conserving way by bonds and junctions. This not only provides a visual representation of the flow of power through the system but also enables the easy (and automatic) derivation of the governing equations. This modeling technique has been extended to power hydraulics, mechatronics, thermodynamic systems, and recently to electronics and nonenergetic systems like economics and queuing theory. This technique is discipline independent, and multidomain systems such as mechatronic systems can be just as easily modeled as purely mechanical or electrical systems. For example, as Fig. 1 shows, the bond graph representation of an electrical RLC circuit is the same as that of a mechanical spring-mass-damper system. Derivation of system equations is so systematic from the bond graph that it can be easily made algorithmic. These bond graph-based models can be established very quickly and can also be altered quickly to simulate alternate designs. Several commercial software tools are available that may be used to model systems and simulate their behavior. Among these tools are 20-Sim [6], Camp-G [7], SYMBOLS 2000 [8], and AMESIM [9].

The topics covered in this class are the following:
1) introduction to mechatronic system modeling: systems, subsystems, components;
2) multiport systems and the concept of bond graphs;
3) simple mechatronic elements in systems and construction of bond graphs;
4) causality and governing equations;
5) system models and computer simulation: introduction to 20-Sim, a bond graph-based system simulator;
6) modeling and analysis of linear systems: interpreting simulation results;
7) modeling sensors: capacitive, resistive, and inductive sensors;
8) modeling actuators: motors, hydraulic actuators;
9) modeling automotive mechatronic systems, vehicle dynamics;
10) control systems and transducers;
11) modeling nonlinear systems.

C. Course Requirements

Student homework assignments in this course include computer simulation assignments on the topics covered in class. There are two exams—a midterm as well as a final. There is also an end-of-term project that is different for each of the different groups. Project deliverables include a proposal presentation, a final report, and a final presentation. For the first three offerings, a textbook by Karnopp et al. [5] was used in this class. One of the authors has since written a text for this course [10] that is going to be used in future offerings. The simulation exercises are performed using 20-Sim [6], a bond graph-based simulation tool.

During the four years that the course has been offered, students completed several very interesting projects, including the following:
• bond graph analysis of active suspension in car;
• bond graph analysis of closed loop feed drive system of CNC machines;
• bond graph simulation of a mouse trap car;
• IC engine-power cylinder modeling;
• study of the deflections of a microelectromechanical system (MEMS) electrothermomechanical actuator;
• bond graph simulation of a simple brake mechanism;
• modeling and control of an inverted pendulum;
• modeling a hydraulic table-lift.

Some of these project topics were proposed by students who had prior experience in a particular area. Others were chosen by students through a search of published technical articles. It is not possible to describe all the projects here in detail, but a sample project is discussed to provide some understanding. More details about some of these projects as well as a listing of others can be found on the Mechatronics Curriculum Project Web site [11].

The project discussed in more detail here is the modeling and control of an inverted pendulum. An inverted pendulum is a highly nonlinear and unstable system. The control mechanism
and control algorithm is very useful for a variety of applications such as design of personal mobility vehicles like the Segway and for stabilizing rockets during their takeoff. Fig. 2 shows a schematic of the inverted pendulum. A PID controller is used to control the vertical position of the inverted pendulum. The angle of tilt of the vertical rod is used in the control algorithm to determine the backward or forward cart movement required to balance the rod.

Fig. 3 shows the bond graph model of the system with the added PID control loop. The control signal $u(t)$ is obtained from the error signal $e(t)$ in a standard PID format as

$$u(t) = K_p e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt}.$$  (1)

Fig. 4 demonstrates system behavior through three important system responses: the angular position of the pendulum, the cart position, and the cart velocity. For the simulation, it was assumed that the control loop was started with an initial angular displacement for the pendulum from its vertical position.

III. SENSORS AND ACTUATORS FOR MECHATRONIC SYSTEMS

The “Sensors and Actuators for Mechatronic Systems” course has been offered as a technical elective for both ME and EE senior undergraduate students as well as to graduate students. It is scheduled for alternating years and has been offered twice so far (2008). In keeping with the project objectives, the course is designed to have a significant hands-on component, requiring students to spend considerable time working on synergistic practical activities involving sensors and actuators in the laboratory, predominantly on their own time. A summary of the course is provided here, and assessment results are discussed in Section IV. More details can be found in [4] and [12].

A. Learning Outcomes

After completing the course, the student should be able to do the following:

1) understand the underlying physical principles of the basic transduction mechanisms of different sensors and actuators;
2) understand the evolution of emerging sensor and actuator technologies such as MEMS;
3) understand the fundamental principles of data acquisition;
4) demonstrate the ability to apply self-directed learning skills by researching a sensor or actuator not discussed in class;
5) demonstrate proficiency in the use of appropriate software tools that permit data and command interaction with common sensors and actuators;
6) work collaboratively across disciplines and cultures on team exercises involving sensors and actuators;
7) demonstrate effective oral and written communication skills in the context of collaborative team exercises involving sensors and actuators.

B. Course Content and Philosophy

The course covers the most common transduction mechanisms of sensors and actuators, including the rapidly developing MEMS area. Different approaches can be adopted in teaching sensors and actuators. Most books in this area organize the presentation around a division of material based on the end application (for instance, measurement of acceleration, force, flow rate, angular position, etc.). The drawback to this approach is that devices that are used in different applications might actually be based on the same physical transduction mechanism relating the electrical and mechanical domains in question. It could be argued that understanding the basic coupling mechanisms first is a better foundation upon which to build knowledge of sensors and actuators as new devices are invented since these devices will likely subscribe to one of these coupling mechanisms. Based on this argument, a fundamentally different and unique approach has been adopted by Bush-Vishniac [13] in which the topical coverage is driven by the fundamental coupling mechanisms that exist. This approach does not require differentiation between sensors and actuators in the development of the basic theory. The downside of this approach is that, by necessity, it is somewhat heavily mathematical in nature, and there tends to be a dissonance with the predominantly experiential course orientation adopted in the work presented here. The very first offering of the course exclusively adopted the second (transduction-mechanisms-based) approach, but the instructor switched to the first approach in the second offering, while still underlining the role of the basic transduction mechanisms in terms of core knowledge. The sensors and actuators discussed were restricted to those of an electromechanical nature in both offerings, which is appropriate to the mechatronics topic.

Here are the topics covered in this class:
1) introduction to the roles of sensors and actuators in mechatronic systems;
2) principles of data acquisition;
3) introduction to LabVIEW and its use in sensor/actuator interaction;
4) transduction mechanisms of common electromechanical sensors and actuators highlighting the connection to practical mechatronics applications
   - Sensors—optical encoder, ultrasound sensor, strain gauge, linear variable differential transformer, Hall Effect sensor, variable reluctance sensor;
   - Actuators—permanent magnet dc motors, stepper motors, and their drive circuitry;
5) understanding the spectrum of a signal;
6) control theory basics;
7) introduction to MEMS.

The discussion of the fundamental principles of data acquisition provided a context for an introduction to LabVIEW [14], which is a graphical programming language that enables the creation of virtual instruments (instruments defined and configured in software) and is widely used in industry. In conjunction with appropriate data acquisition hardware, LabVIEW can be used to acquire and process data from sensors as well as to command actuators based on the results of processing.

C. Course Requirements

Students in the course are evaluated using the following four components: quizzes, homework assignments, a capstone project, and a requirement to pass the online LabVIEW fundamentals exam. The quizzes test concept-level understanding of the theoretical treatment of sensors and actuators provided in the lectures. It is appropriate to emphasize again that a conventional theoretical treatment and associated testing of material would not have been as effective as incorporating extensive laboratory exercises involving working with actual sensors and actuators. Thus, most of the homework assignments assigned during the term involve constructing LabVIEW programs to acquire and process data from sensors and actuators; this choice directly supports the learning outcomes for the course. In light of the extended hours required of students in laboratory activity, it was decided to forgo traditional tests completely. To provide an incentive to learn LabVIEW, the students in the class are required individually to pass the LabVIEW fundamentals exam [15] made available online by National Instruments. The exam is made up of 40 quiz-type questions, out of which students are required to answer 32 correctly in order to pass.

Some examples of laboratory activity centered on the use of LabVIEW are familiarization with analog-to-digital and digital-to-analog conversion using audio signals, determining the position of a robot using its wheel encoder data, controlling the position of a stepper motor and the speed of a dc servo motor, and using data collected from a MEMS accelerometer while in motion to estimate the contour of the path traversed.

The highlight of the course is the capstone project, which requires the student to take on a problem that involves incorporation of a sensor or actuator not directly covered in the lectures or laboratory activities; this need to explore new territory directly addresses the lifelong learning feature of the course outcomes. Furthermore, the problem has to relate or connect with a real-world application. This project is the most rewarding part of the course in terms of results. There have been a total of seven projects developed by student teams over the two offerings of the course, all of which worked successfully. In addition to demonstrating the hardware, a comprehensive report and oral presentation are required at the end of the term.

A discussion of four of the projects is provided below because the project component most effectively validates the success of the “Sensors and Actuators” course.

1) Mobile robot follower: The objective of this project was to demonstrate the concept of autonomous vehicles in a convoy. A small robotic cart with two regular wheels and a caster wheel was used. The two regular wheels were driven...
using separate stepper motors. A set of two infrared sensors were mounted in the front of the vehicle suitably oriented for optimal coverage of the space in front of the robot. The objective was to get the vehicle to follow a target (in this case a cardboard plane) at a fixed distance. The infrared sensors provided information on the distance of the target. This information was used in a simple control algorithm to command the stepper motors to turn the wheels forward or backward as needed to maintain target distance. Fig. 5 is a picture of the vehicle that was successfully demonstrated.

2) Automated windshield wiper system: This project connects with the automated systems that have started to appear in some high-end automobiles, whereby the sweep rate of the windshield wipers is set based on the wetness of the windshield (as established by the volume of rain). Fig. 6 shows a picture of the scaled-down mockup that was constructed to represent the above application. An optical sensor enables the wetness of the windshield to be assessed through changes in the scattering of light, while a servo motor is used to actuate the sweep of the wipers. Once again, a control algorithm is written in LabVIEW that uses the wetness of the windshield (altered during testing by intermittent spraying of water onto it) to establish the wiper sweep rate.

3) Determination of object position using force sensor-based triangulation: A set of three MEMS force sensors are placed under the three legs of a miniature table-like structure made using Plexiglas and short standoffs as shown in Fig. 7. The idea is to use the three force readings and appropriate interpolation algorithms to locate the point of application of a force on the tabletop. This project relates to techniques used to determine “hits” electronically in archery and other target-based sports.

4) Spring-wear monitoring system: The aim of this project was to monitor the elastic condition of a spring after it had been subjected to varying degrees of cyclic loading. The basic infrastructure of the arrangement (shown in Fig. 8) was already available from an earlier project; it uses a dc motor driving a cam to subject the spring to compression cycles. The specific purpose of this project was to redesign/retrofit the arrangement as necessary to accommodate a particular spring, incorporate a linear variable differential transducer (LVDT) to enable direct measurement of the length of the spring, incorporate a load cell to measure applied force, and write a LabVIEW program to record dynamically the applied force versus length.

IV. ASSESSMENT

The assessment of each course was conducted by an assessment expert from the Department of Psychology during the initial offering of the courses. The assessment tools consisted of pre- and post-course surveys followed by a comparative analysis. The questions were about students’ mastery of the fundamental theory and applications presented in the course. In addition, a faculty panel evaluated the final report and oral presentation of the capstone project. Details of the assessment results are available in [4] and will not be discussed here.

To assess the long-term impact of the courses, retrospective student feedback was sought. Responses indicated that the course outcomes were substantially achieved. Here is an excerpt of remarks provided by a student who had taken both courses:

“...Both the courses totally changed my outlook towards my career. I was trying to specialize in Vehicle Dynamics, during which I realized that at some stage the mechatronic system overtakes the whole automotive domain. When I took the classes, I got more interested in Active Safety Systems. ...Even though I am not working...
Fig. 8. Spring-wear monitoring system.

in (the) Mechatronic field yet, but that’s something will be in my quest always. Currently I am also working on my Doctorate thesis, I am trying to involve some mechatronic aspect to it also.”

Here is a comment from another student who took only the modeling and simulation course:

“My company provides system simulation software for leading companies. This software is completely based on bond graph theory and the reason I was able to get this job was because I had taken the mechatronics course and demonstrated a prior experience/knowledge with mechatronics systems. My job involves modeling a range of mechanical, hydraulic, pneumatic and electromechanical systems for various applications (lubrication, fuel injection, valve design, pumps, transmission and powertrain applications).”

Here are excerpts from a student commenting on the Sensors and Actuator course:

“The Sensors and Actuators class was a wealth of knowledge for me. I knew some of the sensors that were discussed in the class, but I felt more comfortable knowing the details of their working. I have benefitted even at work from the class. I had to use LabVIEW software at work to create a software model for a small city, and using digital logic I had to implement a schematic of the power distribution to the various industrial and residential places within the city model.”

V. MECHATRONICS AS A CONCENTRATION AREA AND OTHER SPINOFF ACTIVITIES

A. Mechatronics as a Concentration Area

The importance of mechatronics as a relevant and vital area of expertise is becoming widely acknowledged by both academia and industry, as stated in [1]. In the same article, it has even been suggested that perhaps all mechanical engineers should be mechatronic engineers. The author of another article with the attention-getting but perhaps overstated title “The end of the M.E.?” [16] has, in a similar vein, implied that the traditional ME program needs to be revitalized. That jobs based on just the use of these traditional skills are more likely to be outsourced is a directly stated contention in [1]. This is the promise that mechatronics education brings to the discipline of mechanical engineering in the U.S.

For the discipline of electrical engineering, there are similar gains to be realized. Many products of everyday use are likely to have a mechanical aspect to them and, furthermore, be associated with some form of electronic and/or control circuitry [1]. Thus, incorporation of mechatronics content broadens the playing field for electrical engineers while directly catering to the ABET requirement of interdisciplinary education in engineering programs.

Despite the above realization, although many universities have developed one or two courses in the area, there are still only a very small number of comprehensive mechatronics programs in the U.S. In Canada, Australia, and Europe, there seems to be more enthusiasm for the concept of a more integrated curriculum. It should be noted that mechatronics is associated with enough distinctive content to justify a separate degree, following in the footsteps of other nontraditional and interdisciplinary programs such as systems engineering, biomedical engineering, etc. There are several reasons for the slow start in initiating mechatronics programs. Setting up a new nontraditional engineering degree program, despite ABET’s philosophy of encouraging experimentation, is a difficult task. There has to be enough name recognition and acceptance such that students who graduate with the new degree are able to secure employment; the launch of the new degree program has to be preceded by extensive surveys to gauge employer perception, formulation of plans for accreditation, etc. Additionally, a new menu of fundamental courses might need to be designed and offered. For instance, the traditional sequential courses in circuit theory and electronics (for EE) and statics and dynamics (for ME) might need to be replaced by composite courses that are more relevant to a mechatronics program. These are also needed to create room for the specialized mechatronics courses. However, such new courses require that a critical mass of students be available to justify their offering—the classic “chicken and egg” conundrum.

On the other hand, it is easier to create an undergraduate concentration in mechatronics, where the three mechatronics courses that have been designed can be taken as technical electives or as a graduate specialization. This is the initial path chosen. The existing Master’s program in ME has concentration options in automotive, manufacturing, and thermal sciences, and now mechatronics has been added. Similarly, mechatronics has been added as a concentration in the Master’s program in EE. The EE program has courses in embedded systems, controls, digital signal processing, and so on—all of which complement and add in-depth value to mechatronics expertise. Moreover, the EE Department has a strong interest in research in mobile robotics. Specifically, a joint undergraduate-graduate EE-ME team has, for the past four years, designed and built an autonomous ground vehicle to participate in the Intelligent
Ground Vehicle Competition. This endeavor fits perfectly with the authors’ mechatronics efforts.

B. Other Spinoff Activities

The curriculum development efforts at UDM have led to other activities such as graduate research leading to theses and dissertations and capstone design projects at both the graduate and undergraduate levels. These activities can be itemized as follows:

- design and control of active suspensions for vehicles (completed doctoral dissertation);
- vehicle rollover control using magnetorheological dampers (completed Master’s thesis);
- modeling of variable force actuators for automotive applications (completed graduate capstone design project);
- bond graph modeling of CNC machine feed-drive and biomechanics (completed Master’s thesis);
- reducing conducted transients in automotive windshield wiper motors (completed graduate capstone design project);
- dynamic modeling of a hydraulic power steering system (completed graduate capstone design project);
- modeling the behavior of electrothermal MEMS devices (ongoing Master’s thesis);

VI. CONCLUSION

These two papers (Parts I and II) have reported on a 10-year effort to develop a comprehensive mechatronics curriculum that ranges from outreach activities to graduate school. Starting with a team-oriented, project-based “Introduction to Mechatronics” course at the senior level, the authors also developed modules to introduce hands-on mechatronics activities at first-year and precollege levels. The assessment data from these activities provided the impetus to develop two more advanced courses as well as a concentration in mechatronics at the undergraduate and Master’s levels. Readers are referred to the project Web site [11] for developing information on these ongoing activities.

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REFERENCES


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