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TEACHING A SENIOR-LEVEL MECHATRONICS COURSE IN MECHANICAL ENGINEERING

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ABSTRACT

This paper discusses our common experiences teaching two similar mechatronics courses as senior-level electives offered in departments of mechanical and industrial engineering. Both courses foster an integrated, multidisciplinary, systems-level approach for the design of a physical device or system process, in contrast to the sequential application of mechanical, electrical and computer design techniques. Engineering skills and state-of-the-art technologies are balanced to create a design-oriented course with theoretical content and practical applications. In addition to lecture, there is heavy reliance on simulation studies, in-class demonstrations, project-based assignments, and "case studies" that emphasize multidisciplinary system approaches for design. These approaches have been well received by the mix of mechanical engineering, electrical engineering, and biomedical engineering students enrolled. Our course philosophy, approach and implementation are outlined the paper.

INTRODUCTION

This paper describes two similar mechatronics courses, one offered at Mercer University School of Engineering and the other at Marquette University College of Engineering. Both are elective courses taught in mechanical and industrial engineering programs aimed at the senior undergraduate level and open to first year graduate students. In both courses, students from other engineering departments (electrical engineering and biomedical engineering) are enrolled. At Mercer, the prerequisites include a course in system dynamics, which covers some controls as well as linear circuits. At Marquette, the prerequisites are a course in mechanical measurement and instrumentation as well as a course in circuits. In both of our programs, the mechanical engineering students will also have had a course in machine design, but no formal microcontroller experience.

BACKGROUND

While definitions of mechatronics vary [1, 2], they tend to be similar to the following:

> *Mechatronics is the design of engineering products and systems drawing on the complementary integration of mechanical engineering, control engineering, electronics, and software.*

Building on this general definition, a course in mechatronics must show how designs are improved through an integrated, systems-level understanding predicated on the fundamentals and tools from multiple technical disciplines. In industry and in academia, the boundaries and barriers between engineering disciplines can be significant. A goal of a mechatronics class is to broaden the perspective, and help remove boundaries – artificial or real – by encouraging a blended problem-solving approach that draws upon many areas of technical knowledge and competence.

Examples of mechatronic systems abound, and include auto-focus cameras, CD players, smart toasters, and high-tech toys. In general, machines and processes that rely on sensors, actuators, mechanisms, instrumentation, controllers and micro-processors of various types, sizes, and attributes can be called mechatronic systems. It could be said that large-scale systems, such as industrial plants or the Space Shuttle, with many control loops and interconnections under computer control are at one end of the mechatronics spectrum and relatively simpler devices such as magnetic bearings and even robot manipulators are at the other extreme.

Increasingly, colleges and universities are offering courses in ‘mechatronics’ in their engineering programs. In mechanical engineering departments a mechatronics course sometimes replaces a system dynamics course or alternatively is integrated within a feedback controls course. An informal survey of courses in mechatronics indicates that the content varies widely depending on the department as well as the discipline of interest of the instructor responsible for the course.

Mechatronics courses offered in mechanical engineering departments tend to focus on modeling, controls, and electronics. In some engineering programs mechatronics courses are run in lecture format and emphasize modeling and controls through simulations, while other courses have a laboratory component. When mechatronics is offered as an experimental course, it is generally based on a particular microprocessor or PC-based hardware and software [3-6]. Several engineering programs offer a series of courses in mechatronics, often as an option or certification within a degree program [7-9]. The two mechatronics courses discussed here are offered as elective, lecture format courses open to senior undergraduate and graduate students in our respective mechanical engineering departments.

ENGINEERING FUNDAMENTALS OF MECHATRONICS

Although hardware and software are prone to rapid changes and quickly can become outdated, the fundamental engineering science underlying the successful analysis, design and control of a device, machine, or process has remained relatively constant. The core engineering skills and topics of mechatronics are summarized in Table I. These items are the key topics of the course.

Table I. Core Mechatronic Engineering Topics

- Physical and Mathematical Modeling of Systems
- Characterization and Identification of Dynamic Systems (time-response and frequency-response)
- Sensors: Transducers and I/O Considerations (principles of measurement systems)
- Actuators: Electromechanical (solenoids, DC motors, brushless servo and stepper motors, piezo-actuators), Fluid Actuators (hydraulic and pneumatic), Other (thermal actuators)
- Mechanical Design (linkages, gears, cams, linear motion devices, etc.)
- Analog Electronics (passive and active components; signals and power)
- Signal Conditioning (amplifiers, filters)
- Controls System Analysis (process sequence control vs. servo control, open-loop control, feedforward control, feedback control: analog and digital, PID control, stability and performance, root-locus and frequency-response analysis, transport delays)
- Controls System Design (frequency response design, state-space control, etc.)
- Digital Electronics (digital implementation of control and filtering)
- Controller and Microcontroller Interfacing and Real-Time Programming Issues

HARDWARE VS. SIMULATION OF REAL SYSTEMS

The steps of modeling both single discipline and multidisciplinary systems, such as integrated mechanical and electrical systems, and of algorithm development, e.g., for control of real systems, can be viewed as core foundations of mechatronics. Simulation studies and laboratory investigations both can provide the necessary avenues for learning to build this foundation. While real-world hardware experiences are essential to mechatronics, without question, there are practical realities to running laboratory-oriented mechatronics courses, especially when it is a single elective course. The authors fully acknowledge that laboratory experiences are motivational, pedagogically advantageous, and are crucial for students to fully gain mastery of material. However, to balance limitations on time and resources, we have adopted an intermediate approach involving in-class hardware demonstrations and limited hardware experimentation.

Mechanical engineering students enrolled in our mechatronics courses have not had formal training in programming microcontrollers, and generally have had only limited experience with structured programming. Although implementation experience is difficult without a laboratory, an essential component of algorithm development can be learned in this course. Control logic and algorithm creation can be developed through experiments and by modeling and simulation exercises.

As noted in [3-7], senior-level mechatronics courses taught with a laboratory often build on earlier courses that introduce a microcontroller. Without this as a prerequisite, it adds to the challenge of including laboratories involving embedded controllers in the mechatronic course. As such, the decision was made to focus on modeling and control through the combination of simulation studies and in-class hardware demonstrations.

For students to gain realistic experiences, characteristics of fundamental hardware elements of a control system (e.g., sensors, actuators, signal conditioners, and other mechanical and electrical components and instrumentation) are addressed. In mechanical systems backlash, friction and other nonlinearities are included in the model as appropriate. Real-life controller effects such as dead-bands and saturations also are modeled. Effects of discretization, noise, imperfect filters, are simulated for realistic models of signals and processing. The engineering theory and application of mechatronics delivered through a course focusing on analysis and simulation must incorporate as much realistic modeling of systems, controllers and signals as possible.

While many curricula emphasize laboratories built around microcontrollers, most mechanical engineers (and many electrical engineers) will not face control applications that involve direct programming of microelectronics. Practicing mechanical engineers will most likely encounter mechatronics control via a PLC, motion controller, or process control system, rather than microprocessor level controllers. Thus, it is reasonable not to base a mechatronics senior-level course around a specific commercial controller.

Additionally, as electronic hardware and the associated programming tools (cross-compilers in C, C++, and BASIC) advance, the necessary technical skills to create competitive mechatronic designs change. Within the past several years the requirements of industrial process control have exploded to include several layers of networks (device level networks, multiple controller networks, and data management networks) [10, 11]. It is also important to note that microcontrollers, motion controllers, PLCs and computer hardware with their associated software tools vary greatly by project requirements. However, common among all of these implementations of mechatronics is system design and algorithm development for control of the machine or system.

Both of our courses strongly push model development and simulation studies. Ready access to computer modeling software allows students to experiment (virtually) with their systems, conduct sensitivity studies to parameter changes, and design suitable controllers for their systems. Much of this work can be conducted outside of the class time. Then, in lecture, important features of the models and intriguing insights into the simulation results can be discussed.

DEMONSTRATIONS, PROJECTS AND HOMEWORK

Many skills gained via laboratory experiences can be attained, to a degree, through project work involving modeling and simulation of a real system. Demonstrations, projects and homework are essential means to expose students to practical issues that tie the various parts of mechatronics together. Topics of sampling rate, time delay, sensor selection, signal resolution, control logic, and interfacing devices can be part of homework and projects. In-class demonstrations present the student with visual and tactile proof of concepts.

Demonstrations

In the classroom, both simulation and hardware demonstrations are conducted. Investigations in class using physical hardware and opportunities for directed experimenting with the demonstration hardware are critically important to augment the models and simulation studies of the homework and projects. Directed exercises in class with simulation and DAQ software, run by the instructor in an interactive mode with the students, provide opportunities to highlight special features as well as nuances and caveats of using the software. From these experiences, students gain confidence in the "art" and science of modeling as well as appreciate the limitations of their models to capture real-world behavior.

Familiarization with Mechatronics Hardware Components

As indicated earlier, hardware components in mechatronic systems include sensors and actuators. These are generally available and can easily be brought to class. Doing so demonstrates the wide assortment of possible sensors and actuators for use in a mechatronic system. It also gives students a sense of their size, raises questions about their connectivity to other components, and is a natural springboard for discussion of a myriad of implementation issues (e.g., passive vs. active sensors, power demands of actuators, impedance matching of components, etc.)

Sensors include limit switches, proximity sensors, encoders, potentiometers, strain gauges, force-sensing resistors (FSRs) [12], thermocouples, RTDs, accelerometers, pressure transducers, and solid-state and MEMS-based sensors. Actuators include DC motors, stepper motors, brushless AC motors, solenoids, pneumatic and hydraulic devices, as well as shape memory alloy (SMA) actuators [13] and thermal actuators.

Machines, mechanisms, and their components comprise another part of mechatronic systems. Linkages, gears and gear trains, drives (lead screws), cams and cam-based mechanisms, as well as many other types of mechanisms including four-bar and five-bar mechanisms and specialized designs such as Geneva mechanisms are important for students to know about and use in mechatronic designs.

Electronic components (passive and active), circuits, and subsystems are also used in mechatronic systems. Examples include operational amplifiers, solid-state relays, diodes, microcontrollers, power regulators, oscillators, memory, optical isolators, analog-to-digital converters and other parts that are incorporated into a complete system. Many simple circuits can be built on breadboards and brought to class, or even built in class to help students refresh their understanding of electronic basics. An example would be building passive and active filters on breadboards and testing their performance with a function generator and an oscilloscope. Signal characteristics such as gain, phase, frequency content are easily investigated using this method, and provide an active learning component to the class without requiring a burdensome threshold of hardware skill from the students. Construction of actual hardware validates the engineering analysis and designs as well as provides practical experience.

Interactive Hardware Investigations

Demonstrations are most valuable to learning when the students can interact and experiment with the demonstration hardware. Learning is best for students when accomplished, or verified on their own [14]. A valuable interactive demonstration for student participation is PID position control of a DC servo motor with shaft mounted smooth disks (2-5 cm diameter). Students can introduce position error (twist the motor disk) to see the varying effects of the control types. Proportional (P) control feels like a spring; the restoring torque on the disk increases linearly with increasing position error. Proportional-derivative (PD) control feels increasingly sluggish when the motor disk is moved faster, behaving like a viscous damper. Proportional-integral (PI) control initially seems like P control, until the integrator increases sufficiently to twist the disk out of the student's grasp. If tuned inappropriately the PI controller oscillates. Finally the PID controlled motor provides a more stable response. Students can change the PID gain values, interact with the physical system, and test their understanding.

Complete system case studies and demonstrations are used to introduce students to other mechatronic components, including signal conditioning, power amplification, analog and digital controller designs, and microprocessors. A typical motion control device such as a linear stage axis driven by a servo-motor, shown schematically in Figure 1, is an effective example. Typical position control and velocity control can be demonstrated. With the addition a force sensing device, such as a FSR, the linear stage can be converted to apply a constant force or by using a spring law algorithm (e.g., proportional control for position) a virtual spring can be created. This platform serves well for modeling real systems, and demonstrates many hardware issues such as integrating sensors, amplifier saturation, embedded control loops, signal amplification, filtering, and discretization.

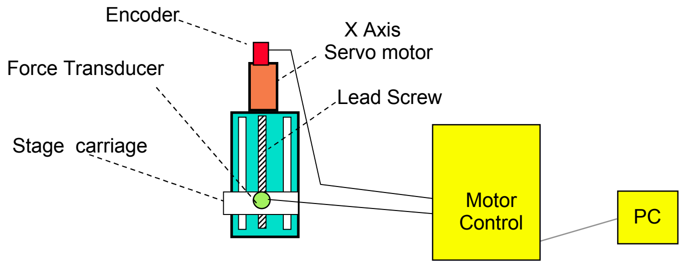

Figure 1. Servo Stage for Position and Force Control

This device demonstrates embedded control loops. In force control applications, the servo stage has position control embedded inside a closed-loop force control. Block diagrams for position control and force control are shown in Figures 2a and 2b. Students model and obtain simulation results to compare with the actual system, as indicated in the side-by-side comparisons in Figures 3a and 3b [15].

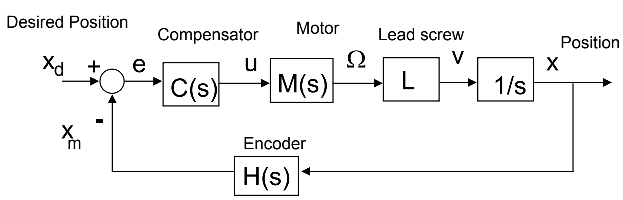

Figure 2a. Block Diagram for Position Control

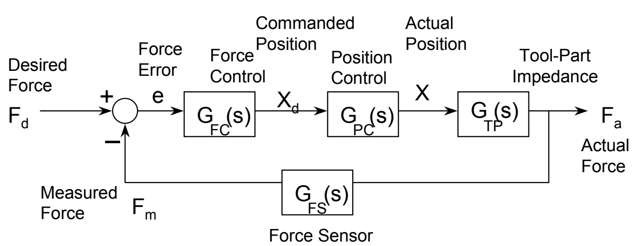

Figure 2b. Block Diagram for Force and Embedded Position Control

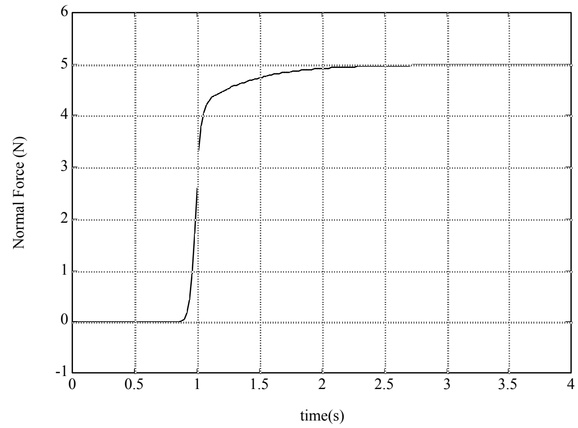

Figure 3a. Simulated Force Step Response

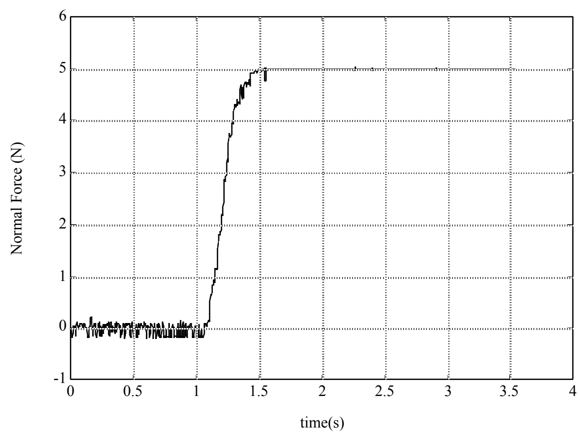

Figure 3b. Actual Force Step Response

Software Investigations

In-class simulations are used to illustrate many of the mechatronic concepts listed Table I. This includes investigations of systems that can be modeled simply as first order systems such as a toilet tank and second order systems such as a car suspension (mass-spring-damper system). Despite their simplicity, these systems are effective for students to understand and provide deep insights into the behavior of actual physical systems. More complex demonstrations include system identification, modeling of components (sensors, actuators, etc.) and integrated multi-disciplinary systems, design of controllers and filters, assessment of stability and relative stability, as well as investigations of complete systems. The classic inverted-pendulum, ball-and-beam balancing, and magnetic levitation [16] experiments are well suited for detailed investigations through simulation. They can be used to study physical limitations, such as noise, time-delays, sampling rate, filtering effects, saturation and other nonlinearities impact the overall system performance and design.

HOMEWORK AND PROJECTS

Homework problems are chosen to reflect practical issues of real-world components and systems. Some of the early homework problems address mechanical considerations and modeling issues in a mechatronics design. Simulation software (e.g., MATLAB and SIMULINK) is incorporated in homework from the beginning. Other problems are case-studies that build in depth and difficulty as the semester unfolds. An example is the design of a high-speed rotating spool and motor drive, considering motor and control parameters, used in fiber manufacturing, such as shown in Figure 4. In this case study, students are given design parameters for the process, as indicated in Table II. Based on these specifications and criteria, students are asked to make spool design decisions and model the machine consisting of a spool, a motor and a drive system, as well as determine control, sensor, and electronics limitations.

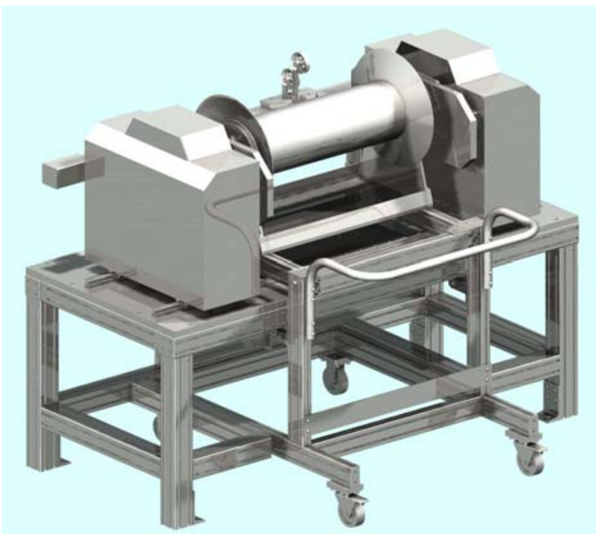

Figure 4. High Speed Fiber Spooling Machine

Table II. Case Study Specification

- Spool linear velocities from 0.1 m/s to 50 m/s
- Spool up to 10^6 m of 0.25 mm diameter fiber assuming 75% packing density
- Mass of fiber is approximately 7 kg per 100 km
- Decelerate to a stop from a linear fiber speed of 50 m/s in 6 seconds or less.
- Motor controller output is 0 to 10 V_{DC}.
- Motor power amplifier is limited to 20 A peak, 15 A continuous at 24 V_{DC}.
- 2500 line quadrature encoder for shaft position.
- Motors available [17]

	Max Speed RPM	Torque-stall N-m	Torque- peak N-m
Motor A	2000	9.15	24.86
Motor B	3800	4.41	12.32
Motor C	3000	16.04	96.04
Motor D	3000	23.39	118.6
Motor E	3000	31.75	163.8

Machine Tool Case Study

Other real-life examples and case studies include control applications in machine tools, process control, and experimental models. Real data from actual systems are used in many homework sets. An example of an extended case study is the control of a machine tool carriage using a DC motor in series with a rack-and-pinion mechanism, shown in Figure 5. The input can be either an ideal current source, $i_s(t)$, voltage source, $e_s(t)$, or an effective duty cycle (0 to 100%) of pulse width modulation (PWM). Parameters include the motor torque constant K_m, winding resistance R_m, motor armature inertia J_m, motor shaft damping B_m , shaft stiffness K, pinion gear inertia J_g, pinion gear radius r, rack (bar) mass m_b , and carriage mass m_c. The nonlinear friction in the rack-and-pinion mechanism can be represented by the single nonlinear damping force F_{NLD} characteristic shown in Figure 6. The output is the velocity of the carriage, v.

Students are asked to:

- Develop a state variable model.
- Determine the equilibrium values of the state variables for a steady input of a specific input current, voltage, or duty cycle.
- Linearize the state variable equations, and from these equations find a linear input-output differential equation.
- Develop a simulation block diagram of the nonlinear and linearized state variable model. A typical bock diagram using SIMULINK is given in Figure 7.
- Investigate and compare the system behavior for different inputs (e.g., step, ramp, harmonic inputs).
- Design a controller and/or modify system parameters to meet certain specifications.

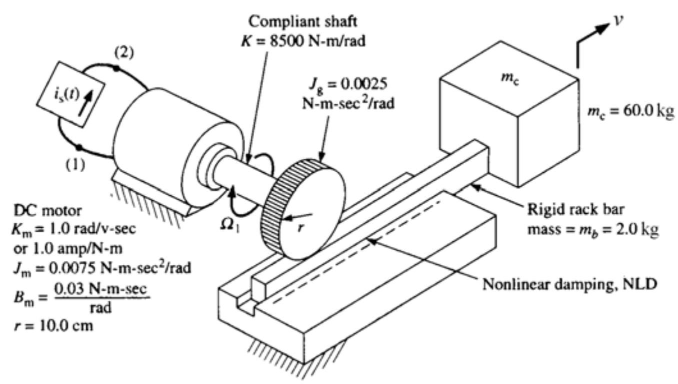

Figure 5.Rack-and-Pinion Carriage Drive with a DC Motor (adapted from [18]).

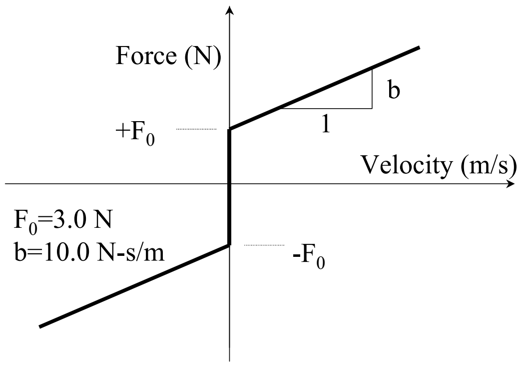

Figure 6 Nonlinear Damping Force (F_{NLD}) Characteristic for the Rack-and-pinion Mechanism (adapted from [18]).

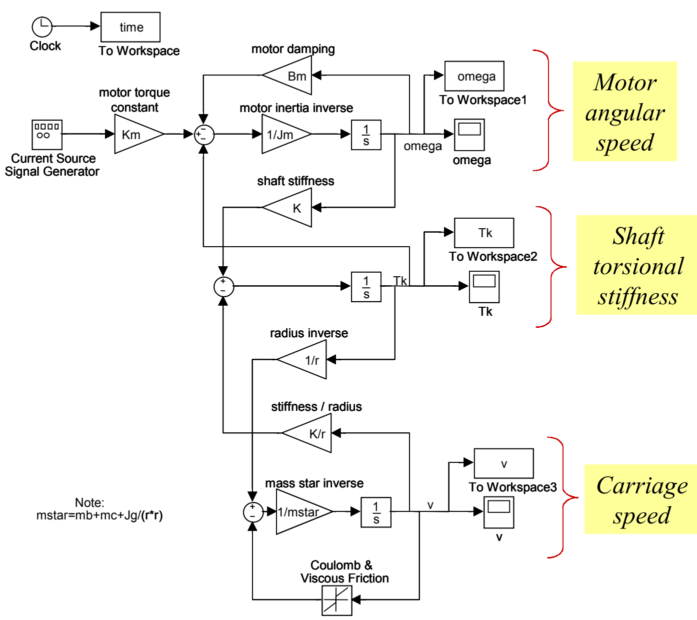

Figure 7. SIMULINK Block Diagram Model of Rack-and-pinion Carriage Drive with a DC Motor.

Semester Project

An in-depth semester project builds upon the extended case studies. In this project, students, teamed in groups (of 2 to 4 students) propose a real-life system to design, model and control. Upon approval of an initial proposal, the students develop a model of their system using real component data. Limitations such as saturation, friction, backlash, and other significant nonlinearities must be modeled from actual component data sheets. By using actual component data available from vendors (from web sites and catalogs), students obtain real data for their designs and hopefully see learning extend beyond the classroom.

Students verify the model of their system through simulation studies. Control techniques are then applied to improve system outputs to meet their project objectives. Again, simulations are performed to validate the resulting system performance.

Students with sufficient background in microprocessors are encouraged to develop their own hardware project using prototype development systems [19, 20]. An example of a hardware-based project is the design of a toy car steering control involving the use of motors, gear trains, sensors, data acquisition, control and power. Projects have included: electric power steering, active suspension, fuzzy cruise control, fuel injection control, positioning for outboard motors, and cooling control for internal combustion engines.

Graduate students and advanced undergraduate students study more complex models with multiple inputs and outputs (MIMO systems). An additional requirement for the graduate students is that, they perform a literature survey in an area of mechatronics (*e.g.,* MEMS sensors, model reference adaptive control, neural network control) and perform detailed modeling studies throughout the course.

SUMMARY

This paper describes two similar mechatronics courses, one offered at Mercer University and the other at Marquette University. Students learn the critical mechatronics engineering fundamentals through modeling exercises, interdisciplinary simulation studies, and hardware demonstrations and investigations. One message of the paper is that without an "official" laboratory component, it is still possible to introduce essential concepts and explore practical issues associated with mechatronics analysis and design. Students gain a fundamental understanding of dynamic systems, sensors, actuators, control components and algorithm development using modeling and simulation studies coupled with in-class hardware demonstrations and investigations. By virtue of the system-level, integrated, multidisciplinary design approach, students learn to appreciate engineering trade-offs in the design of mechatronic systems through homework, case studies, and semester projects.

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