Integrating Sensing and Information Processing in an Electrical and Computer Engineering Undergraduate Curriculum

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Abstract - **The Department of Electrical and Computer Engineering at Duke University has completed a full-scale redesign of its undergraduate program based on the theme of *Integrated Sensing and Information Processing*. This theme provides a coherent, overarching framework that links principles of ECE to each other and to real-world engineering problems. The cornerstone of the new ECE curriculum, *Fundamentals of Electrical and Computer Engineering*, has been designed to provide students with a holistic view of ECE and as a roadmap for the remainder of the curriculum. Each of four follow-on core courses integrates lateral and vertical connections to other courses through the use of thematic examples. Following the five core courses are seven ECE technical electives that include a theme-based culminating design course. Early and pervasive experiences with open-ended design and project-based learning are primary objectives of the curriculum redesign. Regression analyses of course/instructor evaluation data and descriptions of student design project complexity after the curriculum redesign are presented indicating a positive impact of the curriculum redesign on student learning.**

Index Terms – Integrated sensing and information processing, Theme-based curriculum redesign, Department Level Reform

INTRODUCTION

During the two year period 2000-2002 the undergraduate curriculum in the Department of Electrical and Computer Engineering at Duke University underwent an extensive assessment including individual course and lab content by an industrial advisory board and the collective Duke ECE faculty, in-depth interviews with students at all levels by a private sector educational consultant, several forms of course and laboratory student surveys, and surveys of exiting seniors and alumni. Six areas for improvement were identified including a need to: 1) provide a coherent, overarching framework that integrates basic principles of ECE to serve as a roadmap through the curriculum, 2) provide more guidance, through earlier, broader exposure to ECE, to assist students in the selection of technical areas of concentration, 3) present a more balanced coverage of fundamental areas of ECE, 4) enhance the flexibility of technical elective requirements, 5) broaden design opportunities, and 6) better integrate the use of computational tools.

Research into effective engineering student learning suggests that: 1) modern engineering education should provide an early focus on real-world problems [1], 2) laboratory experiences should not be prescriptive or formulaic, but should include design-oriented projects [2], 3) active learning techniques and innovative use of technology in the classroom can increase student engagement [3], 4) Electronics, systems/information processing and computer science represent the three central topics of ECE [4], and 5) engineering education must be *relevant* to students' lives, *attractive* to students with diverse backgrounds, and *connected* to the needs of the broader community [5].

In response to the extensive assessment of its undergraduate curriculum and consideration of the emerging body of research into effective engineering student learning, the ECE Department at Duke University committed to redesign its undergraduate curriculum centered on the theme of *Integrated Sensing and Information Processing* (ISIP). The timing of this decision (2002) coincided with the National Science Foundation solicitation for Department-Level Reform of Undergraduate Engineering Education Planning Grants. The ECE Department applied for and received a one-year planning grant in 2003 and a three-year implementation grant in 2004 (PI: L.M. Collins). The implementation of the new core began in the spring of 2006 with a pilot offering of Fundamentals of ECE and a full core offering in the fall of 2006. As the new core continued to evolve, upper-level technical electives, including design courses, were modified to align with the philosophy and ISIP theme of the redesign.

This paper presents details of the curriculum redesign process, the current state of the curriculum, future directions and sample assessment results indicating positive impact on student learning.

CURRICULUM REDESIGN PHILOSOPHY

The objective of the redesign was to develop the best possible ECE undergraduate curriculum for Duke students. This objective was accomplished by threading the theme of Integrated Sensing and Information Processing (ISIP) through every core course and technical focus area including the culminating design experience. The ISIP theme reflects the active research areas of the majority of the ECE faculty, embodies the key concepts of all critical components of ECE, and broadly reflects the current state and future of the field. The ISIP theme-based structure enables coherent, lateral and vertically integrated connections between each course. These connections provide immediate relevance to what students are learning, increasing their interest and engagement. Other ECE programs considering the redesign of their undergraduate curriculum might consider a theme-based approach using a theme that reflects their unique faculty expertise.

Project-based learning (PBL) of engineering has received significant attention in the literature world-wide recently as an effective vehicle for providing exciting, relevant and meaningful contexts for learning engineering concepts. PBL enables students to practice self-directed learning, which naturally leads to life-long learning. By placing the responsibility of learning on the student, it promotes the ability to adapt to change [6]. The ability to adapt to change is vital to the success of engineers in the 21^{st} century [7]. One of the goals of the curriculum redesign was to establish lab experiences for *all* core courses with tightly-coupled integration between lecture and lab. All core courses now have labs with ISIP theme-based projects and varying degrees of open-ended design.

A hallmark of the ECE curriculum at Duke is its flexibility enabling students to pursue a second major or a semester abroad. This increased flexibility is attractive to students.

REDESIGN OF THE CORE CURRICULUM

There were three main goals specifically associated with the redesign of the core curriculum; 1) develop an ISIP theme-based introductory course that provides a rigorous, yet broad introduction to ECE, a meaningful design experience, and a roadmap for the entire curriculum, 2) restructure the core curriculum to provide more balance considering the three central topics of ECE, and 3) develop hands-on, ISIP theme-based lab experiences for all core courses with open-ended design and project management as appropriate.

Figure 1 illustrates the structure of the ECE core curriculum before and after the redesign. Prior to the redesign, the first course was \ *Electric Circuits*, which had a highly prescriptive lab with standard experiments that exercised the use of test and measurement equipment in the context of verifying DC and AC circuit principles. The content in the Circuits course was used primarily as prerequisite material for the *Devices* course, which in turn provided prerequisite content for *Integrated Circuits*. Concurrently, students took various combinations of *Signals and Systems* (minor lab experience), *Digital Logic (lab)*

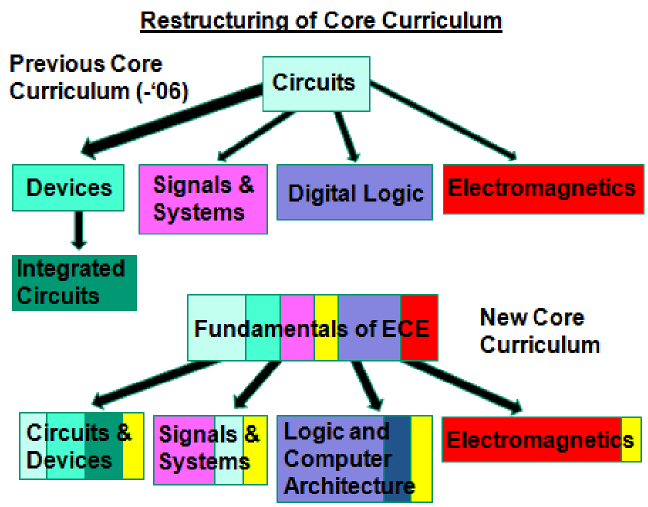

FIGURE 1
ECE CORE CURRICULUM BEFORE AND AFTER REDESIGN.

and *Electromagnetics* (no lab). In the new core curriculum, the first course, *Fundamentals of ECE*, provides a rigorous, yet broad introduction to ECE providing students with a holistic view of ECE by introducing concepts spanning how to interface sensors and systems with the physical world, how to transfer/transmit energy/information, and how to extract, analyze and interpret information. A roadmap for the remainder of the curriculum and a spring-board launching students into four follow-on core courses are provided by introducing these concepts in the context of an ISIP theme-based Integrated Design Challenge. Each semester the theme of the Integrated Design Challenge is changed. Examples of themes, which are intended to provide a meaningful context with connections to either students' everyday lives at Duke include: Smart Home, Duke Real World, Duke Clue, Alice in Wonderland, Star Wars, and Mission Possible. Details of *Fundamentals of ECE* are presented in [8]. One consequence of rebalancing the core curriculum is the reduction of circuit-centric content. The color code, including hue, in Figure 1 indicates approximate percentage of topical coverage. The arrow widths indicate relative support in prerequisite content including project management skills (e.g. ability to work in teams and effective use of Gantt charts).

The new *Microelectronic Circuits and Devices* course was designed considering that this may be the last course a student will ever take in the area of devices and integrated circuits. The approach taken was to vertically integrate the content from device materials, to device fabrication processes and technologies, to transistors as building blocks of integrated circuits, to electronic systems of integrated circuits. Experientially, students measure devices as they are discussed in lecture and learn the principles upon which electrons and holes in semiconductors behave so that they exhibit the desired characteristics of transistors and how to exploit these characteristics in integrated circuits. During the first half of the semester, the lab is divided in two unequal parts. The smaller first part is devoted to measuring and characterizing transistors in integrated circuits and how to use measurements to parameterize the devices in HSPICE. The second part is an introduction to the characterization of analog and digital integrated circuits. An objective of this course is for students to know what an engineer working in the field of devices and circuits does. Students maintain an engineering notebook as a technical diary used in filing and defending mock patents, and they address the ethical issues of having their notebook authorized and notarized by their colleagues. The second half of their experience is completing an ISIP theme-based design project that includes the sensing and transfer of information. As an example, students use infrared remote devices to initiate a sensing event such as temperature, pressure, or wind speed, perform A/D and send this information back to a remote for display. Custom PCBs are provided. Students form companies and come up with a product to sell based on the lab project and then write a high level description of their project and a brief venture capital proposal describing the product they want to fabricate and sell. Student teams make presentations to the class who represent the customers. The instructor plays the role of venture capitalist. Students are required to develop and update a project Gantt chart and a budget. The two weekly class meetings are split. One session is devoted to answering questions that arise from lab and are highly interactive. The instructor steers the conversation to topics that need to be covered in the class while answering the questions. The questions are predictable and the response to each question is a mini lecture. The other class period is devoted to students providing technical updates. The course culminates in demonstration of the final projects and a detailed technical report.

Digital Logic had the advantage that prior to the redesign the lecture and the lab had been well integrated. It was a strong, practical, hands-on course. By standards of peer institutions the pace was a little slow. The intent in reforming the class was that the pace would be increased for the classical combinational and sequential logic circuits to enable students to learn CAD tools. This in turn would enable students to do more substantial projects sooner. By covering classical material very quickly and giving students a more thorough exposure to concepts of programmable logic, it opened up time to cover VHDL in much greater depth than was previously possible. Although it was not part of the original plan, it became clear that students were advancing so quickly in the lab that a final design project was feasible. This became evident when the instructor observed that projects being completed by sophomores were comparable to the projects being completed by current seniors from the previous curriculum. The ability to program an FPGA or other logic device to handle the details of a machine with many dozens of states combined with the existence of cheap boards whose manufacturers allow layout software to be downloaded, and decent CAD tools that allow one to turn arbitrary finite state machine designs into CAD files onto cheap chips, freshmen and sophomores are able to design sophisticated finite state machines.

The *Electromagnetics* course previously had no lab component. The redesign of this course had two primary objectives: 1) create new course content dealing with antennas and antenna arrays with examples of practical systems utilizing these concepts, and 2) develop a sequence of lab exercises culminating in the design, simulation and measurement of a practical, functioning antenna. The new version of this course includes two weeks of content devoted to antennas and antenna arrays. Four lab experiences were created: 1) Transmission line transients, 2) Sinusoidal steady-state on transmission lines, 3) Electrostatic crosstalk, 4) Antennas. In the last lab students design and build 2.5 GHz antenna from a Pringles can that will work with an 802.11b wireless networking system. After completing the design and building the aperture antenna, students measure: 1) the antenna feed point impedance to confirm that it radiates maximum power at the desired frequency, and 2) the antenna's beam width to estimate its directivity. These real-world connections make the concepts immediately relevant, improving student engagement and learning.

In a traditional introductory signal processing course, the concepts are often presented in a very mathematical and abstract format. This can discourage students from further exploration because of the apparent irrelevance to real-world problems. Although the previous version of the *Signals and Systems* course included a minimal lab experience, the primary focus was on the use of MATLAB to implement and explore various signal processing algorithms. One of the primary goals of the redesigned course was to provide students with a variety of hands-on, application-driven experiments designed to give students the opportunity to apply signal processing theory to realistic challenges. Capitalizing on students' exposure to MATLAB programming in previous courses, the Texas Instruments' C6713 DSK digital signal processing (DSP) board, which can be programmed using SIMULINK and MATLAB, was chosen as the basic platform for the new laboratory experiments. The experiments include: 1) Audio Signal Processing, for which students design and implement algorithms to create audio effects such as echo and reverberation, using their own music and voices as sound sources; 2) Touch-Tone Phone, for which students simulate the dual-tone multi-frequency (DTMF) phone system; 3) Sampling and Aliasing, for which students experiment with a variety of audio signals, such as voice, music, and pure tones; and 4) Voice Scrambler/Descrambler, for which students explore the effect of modulation on speech and music signals. In a final lab project, which provides a particularly strong thematic link to the Microelectronics Circuits and Devices core course, students build a simplified AM radio receiver from basic circuit components and observe the signals after each of several stages of processing. Additional details of this course and lab are reported in [9].

UPPER-LEVEL TECHNICAL ELECTIVES

Prior to the curriculum redesign, students were required to select two areas of concentration and take two courses within each area. Areas of concentration include: 1) Computer Engineering and Digital Systems, 2) Signal Processing, Communications and Control Systems, 3) Solid State Devices and Integrated Circuits, 4) Electromagnetic Fields, and 5) Photonics. In order to increase the flexibility of the curriculum, while preserving depth in at least one area and breadth, the ECE Department relaxed the distribution requirement of the four concentration courses to the following choices: 1+1+2, 2+2, 3+1. Following are examples of upper-level technical electives with brief descriptions of how their content was modified to align with ISIP theme-based curriculum redesign.

Linear Control Systems has undergone significant changes in content in order to leverage the successes of the new core curriculum and to expose students to the sensing and information processing aspects of control theory. The most significant change in the course has been the addition of a weekly lab session. With the addition of a 3-hour lab period, three important components were added to the course. First, hands-on lab exercises involving analysis and design of electrical control systems were added. Second, several lab sessions were set aside to introduce important computational tools. Finally, three of the lab sessions were set aside for midterm examinations.

For the hands-on laboratory experiences, students use their knowledge of data acquisition systems from their first-year computational methods class to monitor and control basic electrical systems. These systems are tied in to the transfer functions discussed in class, giving students tangible experience with instrumentation, determining and maintaining system stability, measuring steady-state errors, and designing electrical controllers. In one specific example, "Unity Feedback Systems and Proportional Control," students use cascaded op-amps to build a closed-loop system including a controller and a simulation of a two-pole plant. By varying the component values, students are able to explore several of the theoretical concepts discussed in previous lectures. The unity feedback lab capitalizes on the second addition to the course - exploration of computational tools. Students learn how to use the MATLAB Controls Toolbox and programs such as LTIView and SISOtool to efficiently analyze systems so they can spend more time on design. During the unity feedback lab, students use SISOtool to model the closed-loop system they build and to find appropriate gain values for a variety of desired transient and steady state error values. They also use the Simulink system - first introduced in *Signals and Systems* - to better visualize information flow and signal processing in a closed-loop system. The Simulink program allows students to monitor and display a host of intermediate signals, introduce models for common sources of error, and examine nonlinearities quickly and efficiently. The final addition to the course - exams taken during the laboratory meetings - students are given sufficient time to truly analyze and design control systems while also being allowed to use computational tools from the class. Test questions for an exam given during a lab period and in a room equipped for computer use can include multiple aspects of information processing for an integrated control system.

Digital Image and Multidimensional Signal Processing introduces students to the theory and methods of digital image and video sampling, denoising, compression, reconstruction, stenography, and analysis. The ISIP curricular theme is interwoven throughout the course. Key underlying questions are stressed such as: Given a data collection model, is the proposed processing technique optimal? How can its performance be characterized? Could an alternative mode of data collection yield higher performance?

A key component of the course is the completion of ISIP theme-based group projects. For example, in a computed tomography (CT) volume segmentation project, students used tools learned in class to process data sensed by a CT scanner. That processed data can be used by the original researchers studying pediatric cartilage development to guide future sensing efforts with minimal risk of missing important features. Another student group studied novel designs of spectral imagers, which allowed indirect measurements of spectral images to be collected and resulted in a challenging inverse problem. By studying the inverse problem solution and the quality of the reconstructed spectral images, students quantitatively assessed the impact of the novel sensing approach integrated with image processing techniques and compared their results from more conventional sensing systems. In a third student project, a team studied the emerging framework of "compressed sensing", which deals with reconstructing large images or other signals from a limited number of indirect measurements. This allowed the students to examine the tradeoff between sensing resources such as detector array area and processing issues such as computation time and noise sensitivity.

Computer Network Architecture and *Wireless Networking and Mobile Communication* are two courses in the computer engineering and digital systems area of concentration. Highlighting this particular pair of courses exemplifies building sequential, vertically integrated ISIP theme-based, upper-level courses. *Computer Network Architecture* introduces the building blocks of a computer network using the internet as a case study. In class they learn the theory (e.g. TCP/IP), and then when they access websites or use Instant Messenger (IM) they are able to understand the end-to-end communication process. Groups of students are formed into teams and build their own instant messaging system and use this custom system to communicate during the subsequent mini-project that involves taking a piece of the internet and constructing it on their own. At the end of this course students are able to speak fluently about all of the building blocks of a computer network (entire stack of protocol layers). Near the end of the course, a roadmap to wireless networking is provided by the instructor to pique the students' interest in the follow-on course *Wireless Networking and Mobile Communication*, which was created in the spring of 2007. The roadmap involves student consideration of how to make the last link (or set of hops) entirely wireless. The instructor prompts the students with a set of questions but does not provide the answers, thereby providing an interest "hook" or "teaser." *Wireless Networking and Mobile Communication* begins with a tree class primer of *Computer Network Architecture* emphasizing the (approx.) 15 key concepts that one must understand well before considering how a wired network can be transitioned to a wireless network. The students are asked to consider how to make the transition to a wireless network as the instructor points out the inconsistencies and errors in the student's thinking. This is the essence of inquiry-based learning – placing students in situations where they must grapple with their own misconceptions, taking on the responsibility for their own learning, as the instructor fuels the learning process by pointing out the discrepancies between the student's explanation and evidence. The first 6-7 classes are devoted to this process rather than lecturing on new course content. In the process the students are steered by the instructor to key papers in the literature that addresses the content necessary to answer the students' questions. The entire course is devoted to a team-based, open-ended wireless networking/mobile communication project. There are two primary course content foci: wireless networks, which contains a range of subnetworks e.g. SIM (WIFI); and sensor networks. The focus on sensor networks examines devices called motes, which contain an integrated platform with a microprocessor, a sensor, and a wireless radio enabling the sharing of information across multiple sensors forming an autonomous, programmable, collaborative network.

CULMINATING DESIGN EXPERIENCE

There are currently six approved ECE Design Electives. As part of the curriculum redesign process, all of the design courses are being aligned with the ISIP theme and redesign philosophy. Following is an example.

Opto-Electronic Design Projects was taught for five years prior to the curriculum redesign and was dramatically modified to incorporate the ISIP theme and redesign philosophy. The pre-redesign version was focused on a single project (gigabit Ethernet switch that evolved into a switch with a wireless interconnect) that all groups designed, simulated, built and tested to industry defined standards and specifications. To align the course with ISIP theme, the instructors have completely changed the design project to a sensor and sensor interface circuit that integrates photonics, colorimetric sensing and microsystems. The students have to design their optical systems both from a geometrical optics and optical throughput link budget perspective. The students are designing the circuits and boards to drive the optical emitters and detectors. Three chemical sensing processes are performed to determine water quality: total hardness, alkalinity and chlorine content. Duke's Occupational and Environmental Safety Office provides lectures dealing with the safe handling of toxic chemicals (e.g. ammonia). Students reverse engineer a Pasco colorimeter as the "gold standard," against which they will have to compare their own colorimeter design results. The absorbance at four wavelengths are digitized to provide a signature for the sample under test. Every group must complete the base project which includes the colorimeter and a wireless interface (ZigBee 802.15.4 IEEE standard). In addition to the base project are a set of challenges that individual groups may select to undertake.

Some elements of the course have remained unchanged as a result of the curriculum reform such as safety, techniques for and practice with surface mount soldering, use of Gantt charts for project management, and weekly presentations.

REGRESSION ANALYSIS OF STUDENT SURVEYS

Evaluation results of our curriculum redesign are emerging with the first class to have experienced the full-scale redesign graduating in May, 2009. The Tables 1-5 present regression analyses of core course student end-of-course responses to the statement: **This course increased my ability to design a system, component or process to meet desired needs.** All responses were on a five point scale. The data was obtained over the period Fall 2003 – Spring 2006 for the "before" values and the period Fall 2006 – Fall 2008 for the "after" values. All data comparisons except for *Fundamentals of ECE* include multiple instructors. The *Fundamentals of ECE* data utilized values for only a single instructor to eliminate instructor as a factor.

TABLE 1
ANALYSIS OF INTRO TO CIRCUITS VS. FUNDAMENTALS OF ECE

N = 58	N = 108
Mean before 3.53	Mean after 4.49
St Dev before 0.81	St Dev after 0.68
p = 5.691E-12	

TABLE 2
ANALYSIS OF DEVICES VS. MICROELECTRONICS CIRCUITS AND DEVICES

N = 60	N = 84
Mean before 2.97	Mean after 4.35
St Dev before 1.28	St Dev after 0.60
p = 1.664E-11	

TABLE 3
ANALYSIS OF DIGITAL LOGIC VS. LOGIC AND COMPUTER ARCHITECTURE

N = 71	N = 143
Mean before 3.64	Mean after 4.39
St Dev before 0.89	St Dev after 0.77
p = 9.45921E-09	

TABLE 4
ANALYSIS OF ELECTROMAGNETICS VS. ELECTROMAGNETICS

N = 75	N =101
Mean before 2.35	Mean after 3.17
St Dev before 1.36	St Dev after 1.20
p = 3.021E-05	

TABLE 5
ANALYSIS OF SIGNALS AND SYSTEMS VS. SIGNALS AND SYSTEMS

N = 86	N = 97
Mean before 3.61	Mean after 4.13
St Dev before 1.08	St Dev after 0.85
p = 2.069E-04	

The number of student responses (N) is provided for each sample group along with the sample mean, standard deviation and resulting one-tailed p-value. The one-tailed p-values were computed since the underlying question is, “Did the curriculum redesign cause a significant change in the mean value of the student response?” In every core course the results are highly significant. These results indicate that students perceive improvement in their ability to design a component or system across the entire core curriculum.

CONCLUSION

The ISIP theme-based approach to the curriculum redesign continues to unite the entire faculty by directly connecting their collective and individual expertise with their course content and providing motivation to understand and contribute to the content of courses feeding their own course and to those courses that follow. The ISIP theme provides a coherent, overarching framework that links principles of ECE to each other and to real-world engineering problems. The data available for evaluation is emerging with the first cohort graduating in May of 2009. Initial evaluation results indicate that students perceive significant improvement in their design ability across the entire core curriculum. Much work still remains to assess the impact of the curriculum redesign on student learning and the attainment of the ECE Department’s educational objectives.

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