Experiential Learning of Complex Engineered Systems in the Context of Wireless Sensor Networks

Abstract

There is a strong need for the reform of engineering education in order to prepare students for one of the great challenges of this century: to understand highly complex problems ranging from health care to geoengineering and to synthesize the necessarily complex-engineered solutions for them. A multi-university NSF-sponsored collaboration has implemented a modular, web-enhanced course that aims to develop the systems-thinking skills necessary to tackle these problems in the specific context of the engineering of environmental wireless sensor networks (WSNs). As part of this effort, we have developed and are currently testing hands-on experiments that introduce students to the range of engineering skills that are the foundation of WSN engineering. These experiments are based on two platforms: (1) a development board that can be used with a plug-in microcontroller/radio module to prototype simple WSN nodes and (2) a powerful circuit- and system-level simulator. The development board, which we call CLIO, facilitates team-based student projects that can integrate sensors, embedded computing, energy management and wireless communications. The CLIO hardware and software package includes the development board along with experiments that build upon each other. Experiments based on the simulator are complementary, allowing students to explore circuit- and systems-level wireless design parameters and the links between them. This paper describes the capabilities and suggested use for the development board, associated simulation projects, and supporting course material. We also present assessment results based on surveys and focus groups, conducted at two universities in Fall 2009. Two additional universities will be implementing the course with these experiments in Spring 2010. All hardware and software tools and extensive documentation, along with video-based course content, are available through the project website (www.uvm.edu/~muse/). The CLIO boards are being distributed for beta testing at several universities; wider dissemination is being supported by the IEEE Microwave Theory and Techniques Society.

Introduction

This century's problems—energy production and climate change, declining civil infrastructure, plummeting biodiversity, and uncertain supplies of potable water and food, to name a few—pose unprecedented scientific and technological challenges. There is growing recognition that if these problems are to be tackled successfully, innovative approaches are needed to educate engineers with new and different skill sets and attitudes. The challenge to engineering educators is at least two-fold, since we are facing the greatest global need for technological innovation since perhaps World War II at the same time that apathy about technology, and lack of interest in technological careers, has been increasing in developed nations.

We are in the third year of a project called MUSE (Multi-University Systems Education) to develop a new approach to engineering education that addresses these problems head-on. First, we emphasize *systems thinking* [1,2,3,4,5], a set of skills rarely taught in undergraduate engineering curricula, and only learned sporadically and informally in graduate school or industry. Systems thinking centers around the ability to conceive and design complex engineered systems—the very systems that will be needed to solve the problems we face. These systems tend to be multi-layered and multi-faceted, with distributed interacting components requiring interdisciplinary thinking across multiple levels of abstraction.

These systems and the challenges they will address are difficult, intellectually rich, and exciting, and thus are an ideal vehicle for motivating current students and recruiting new students. In this project, we have focused on the technology of distributed, wirelessly networked sensing [6], which will be a critical component of a wide range of complex engineered systems, especially when extended to systems that not only sense, but perform autonomous or semi-autonomous inference, decision-making, and control or actuation. They directly incorporate almost every subdiscipline in electrical engineering, computer engineering, and computer science, from transducer technology to human interface design.

The first year of this project was devoted primarily to developing a capstone course that could serve as a model for constructing portable course content [7]. We have successfully implemented an inverted classroom paradigm [8,9] where students watch video lecture modules on the web, and class time is devoted to discussion and open-ended exploration of relevant, related topics. As we will describe later, all course content is available on the project web site (www.uvm.edu/~muse/).

In the second year of the project, we focused on enhancing and expanding our approach in two directions. First, we improved the video modules to emphasize that the design of distributed wireless sensing/actuation systems is one example of complex system engineering. We also developed a set of experiments that expose students to the range of concepts and tools needed to design a wireless sensor network, and allow them to develop fluency with them in a final design project. In this paper, we describe both of these efforts, their products, assessment results, and our plans for dissemination.

Course Format and Evolution

For the pilot offering we focused on development of video lecture modules covering core material associated with the engineering of wireless sensor networks (Table 1). As we developed the content, and during the course offering, we planned two improvements: better integration of systems thinking, and experiential learning [10,11,12]. Assessment results from the initial offering of the course in Fall 2008 highlighted the need for an experiential learning component to the course. Students felt that providing a hands-on project based aspect to the course would greatly increase their engagement in the content. Many felt that the hybrid nature of the class would have worked better if hands-on opportunities were provided during class time.

In focus group interviews and on course surveys, students expressed the desire “to work with their hands” and to have the opportunity to actually see some of the systems discussed in the modules. One student noted in feedback on an early module, “I’m a hands-on learner. I find it difficult to relate to some of it without working with physical objects.” Another wrote, “I liked the presentations, but I think for me to really understand it I would need to play with it and see it, like in the classes or in my own project.” Based on our experience and these assessment results, we believe that these components are essential in a new generation of systems thinking-oriented courses in any engineering discipline.

Table 1. Learning modules for MUSE capstone course "Wireless Sensor Network Design."

Learning Module	Title
MOT	Motivation
INT	Introduction
SEA	Systems Engineering Applied to Wireless Sensor Networks
TDX	Transducers
ADC	Analog-to-Digital Conversion
RFH	Radio Frequency Hardware
WCC	The Wireless Communication Channel
CTA	Communication Theory as Applied to Wireless Sensor Networks
SNA	Sensor Network Architectures
EMC	Managing the Sensor: Embedded Computing
FIN	Bringing It All Together – Systems Thinking in Systems Engineering

Exposure to complex engineered systems in the context of problems and concepts already familiar to students reinforces both systems thinking and the deepening of understanding of important discipline-specific knowledge. We enhanced our video lecture models to include introductory material that clearly describe the role of that module's topic in complex engineered systems. In a few cases, we re-recorded entire video modules to weave systems-level insights throughout. Finally, every video module concludes with discussion of that topic with a visual representation of a wireless sensor network describing not only its various layers and components, but the different levels of the embedding environment and the problem context (Figure 1).

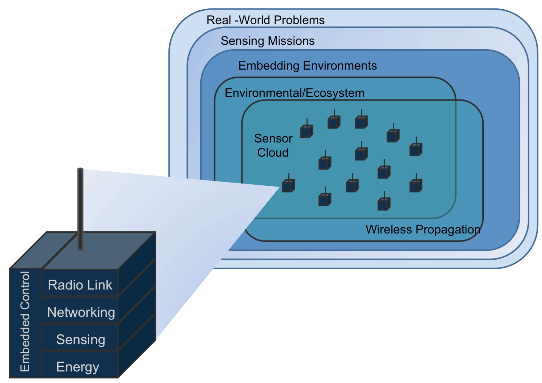

Figure 1. Concept diagram for wireless sensor networks as examples of complex engineered systems. Here, we show them in the context of the environmental sensing application domain.

Experiential Learning

In our experience, today's students, much more than those from previous generations, are strongly motivated by hands-on exploration of concepts. They also respond enthusiastically when they are learning modern analysis, simulation, and design tools that they can expect to use in industry or in graduate studies. We designed a set of experiments under the moniker "Experience the Muse" (ETM) that are coupled closely with the video lecture modules.

Laboratory technology has changed dramatically in the last decade. Our tool selection was determined in part each tool's cost and ability to be used by students anytime and anywhere on a laptop computer. We chose two primary experimental tools. One is the Texas Instruments eZ430-RF2500 wireless development toolkit. The other is the AWR Design Environment (AWRDE) from Applied Wave Research. AWRDE is a second-generation wireless communication design and simulation environment that includes circuit- and system-level packages.

TI eZ430-RF2500 Features

The TI toolkit includes hardware consisting of two wireless nodes each integrating an MSP430 microcontroller unit (MCU) and a TI CC2500 2.4 GHz wireless transceiver chip with antenna, and all needed off-chip components for both. The package also includes an integrated design environment (IDE) called Code Composer Studio for developing software that runs on the MSP430 and controls the MSP430 as well as the CC2500. This development toolkit is available for $50 (we required students to purchase this kit in lieu of a textbook).

We have extended the capability of the eZ430-RF2500 by developing a wireless sensor node development board called CLIO (Figure 2). The eZ430-RF2500 plugs into the CLIO, which provides headers and a prototyping area for easily interfacing digital and analog sensors and other peripherals. CLIO also provides a jumper to switch between USB power supplied via the eZ430-RF2500 programmer and an AA battery pack (the battery holder is attached to the underside of the CLIO board (Figure 2)). The ETM component of the project includes a CLIO experiment with ready-to-run software. The software includes a flexible driver for the MSP430's analog-to-digital converter (ADC) so that students can easily integrate other transducers. We are currently developing a peripheral board called CLIO-STL that provides a low-cost analog light transducer and a modern digital temperature sensor. CLIO-STL provides both plug-and-play transducers for rapid development of a simple wireless sensor node as well as a design pattern for other CLIO peripheral boards that could sense other environmental variables as well as position, movement, vibration, or numerous other phenomena. These boards could be designed by adopting professors for similar courses, or by capstone design teams. The CLIO and CLIO-STL boards, required for later experiments, are available to university and college instructors who adopt MUSE content.

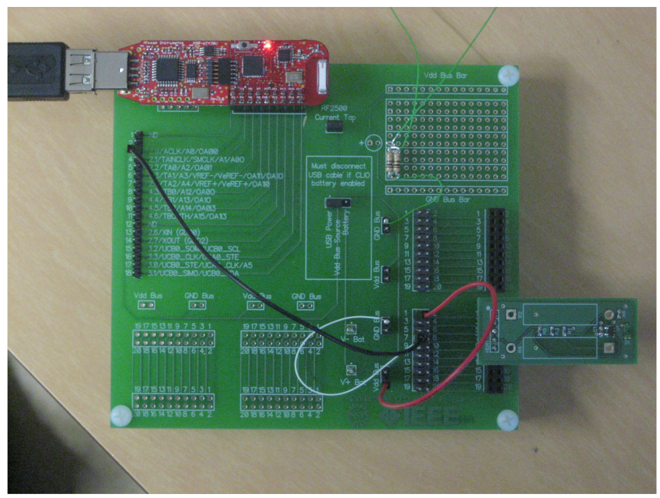

Figure 2. CLIO wireless sensor node development platform, showing eZ430-RF2500 development tool (upper left), peripheral sensor board (lower right), and prototyping area (upper right).

AWRDE Features

AWRDE is an excellent fit for the WSN course because it allows wireless systems to be studied from the component level to the system level. The circuit simulator portion of the design environment, called *Microwave Office* (MWO), is used to teach students about lumped element filter design in one introductory project. Herein, the students construct circuit schematics and can run time- or frequency-domain simulations in order to observe the transient response, network parameters, etc. similar to a Spice-type tool. In a second project, students use the *Virtual System*

Simulator (VSS) part of AWRDE to investigate amplitude modulation. In this case, students are using block-diagram level representations of components such as signal sources, modulators and spectrum analyzers and have the ability to observe the spectrum at any point in the chain. A third project takes further advantage of the design environment to include propagation effects and bit-error-rate analysis. A free copy of AWRDE is available for students and instructors at approved universities.

MUSE Experiments

The experiments (Table 2) are coupled with the video lecture modules (Table 1), so that parts of the in-class discussions are naturally allocated to Q&A about the experiments and how to use the tools.

The experiments are necessarily complicated, and hence are at an appropriate in level for upper-level undergraduate and beginning graduate students. For example, the ADC experiment requires students to think through the process of how a measurable phenomenon, such as light intensity in a forest, becomes a time-tagged number in a computer file, database, or plot. By using a light transducer that captures the fluctuation of light levels from fluorescent fixtures, this experiment reinforces student's knowledge of sampling rates, quantization error from signals and systems courses, and familiarizes them with important tools and techniques including serial communication, MATLAB programming, and the fast Fourier transform (FFT), including important details such as linear and log scaling of data.

Table 2. Summary of "Experience the Muse" experiments.

Experiment Description	**Concepts**	**Tools and Techniques**
CLIO Quick Start	Digital input/output; hardware/software interfaces. Program compilation.	Hardware schematics. Embedded C programming: loops. Integrated development environments (IDE's).
ADC: Sensing and Analog-to-Digital Conversion	ADC resolution. Sampled signals in time and frequency domains. Light transducers.	Embedded C and Matlab programming. Serial communication. Fast Fourier transform (FFT).
RFH-1: RF Filter Design	Scattering (S-) parameters.	Introduction to circuit-level simulation. Insertion loss method of filter design. Low-pass to band-pass transformations.
RFH-2: AM Modulation	Modulation: amplitude modulation. Modulation index.	Signal spectra. Introduction to systems-level simulation.
WCC-RSSI: Channel and Antenna Characterization	Wireless channel attenuation. Path loss, path loss exponent, and multipath fading. Antenna gain pattern. Basic statistics.	Embedded C programming. Single-chip ISM band radios. Received Signal Strength Indication (RSSI). MATLAB. Statistical regression.
CTA-FSK: FSK Transmitter/Receiver Simulation	Modulation: frequency-shift keying. Communication link gains and losses. Thermal noise.	Simulation of noisy communication links.

Assessing the Effectiveness of the Experiments in Enhancing Student Learning

Data were collected to assess the effectiveness of the newly created experiments in enhancing course content and student understanding. Specifically, we were interested in answering the following research questions:

1. How did the students perceive the quality and utility of the experiments?
2. Did the experiments enhance student learning of course content?
3. Did the experiments enhance student understanding of systems thinking?
4. What modifications are needed to improve the experiments to better enhance student learning?

Data collection included both qualitative and quantitative methods to address the research questions including student focus group interviews, student surveys and course assessments.

Student Focus Group Interviews

Students at both institutions participated in focus group interviews at the midpoint of the semester. Students responded to questions about the course format, modules, impact of the course on understanding of wireless sensor networks and systems thinking, and student perceptions of the experiments. External evaluators conducted three focus group interviews with 6-8 students per group. Interviews lasted 40-60 minutes.

Student Surveys

Students at both institutions completed an end-of-course survey to gather feedback on the individual experiments and to assess their impacts on systems thinking and understanding of course content. The survey consisted of a combination of Likert-scale and open-ended questions. Survey respondents included 27 students, representing 17 from UVM and 10 from NAU. Respondents include 13 undergraduate and 14 graduate students.

Student Projects

A team-based student project culminated the course. Students could choose from either a hardware or simulation based project. Example hardware projects included beacon-based synchronization, a sound-level monitoring system and an in situ multipath measurement system. Simulation based projects included the impacts of multipath and convolutional coding on communication system reliability. Student videos for these projects can be found at our project website (www.uvm.edu/~muse/).

Assessment Results

Students responded to questions on the survey about the impact of the experiments on their understanding of wireless sensor networks and on their understanding of systems thinking. Responses were on a seven-point scale with 1 being "not at all helpful in increasing understanding" and 7 being "extremely helpful in increasing understanding." Results indicate that students perceived the experiments as useful in helping them to understand both wireless sensor networks (M = 5.63, SD = 1.12) and systems thinking (M = 5.52 SD = 1.30).

Students also rated the individual experiments on a four-point scale (1 = poor, 2 = fair, 3 = good, and 4 = excellent). Students rated all experiments highly (Figure 3). All students rated the FSK Transmitter/Receiver Simulation lab as "good" to "excellent." RF Filter Design was rated good to excellent by 96% of students, AM Modulation as good to excellent by 92% of students, CLIO Quick Start by 89% of students, Sensing and Analog to Digital Conversion by 81.5% of students, and Channel and Antenna Characterization by 78% of students.

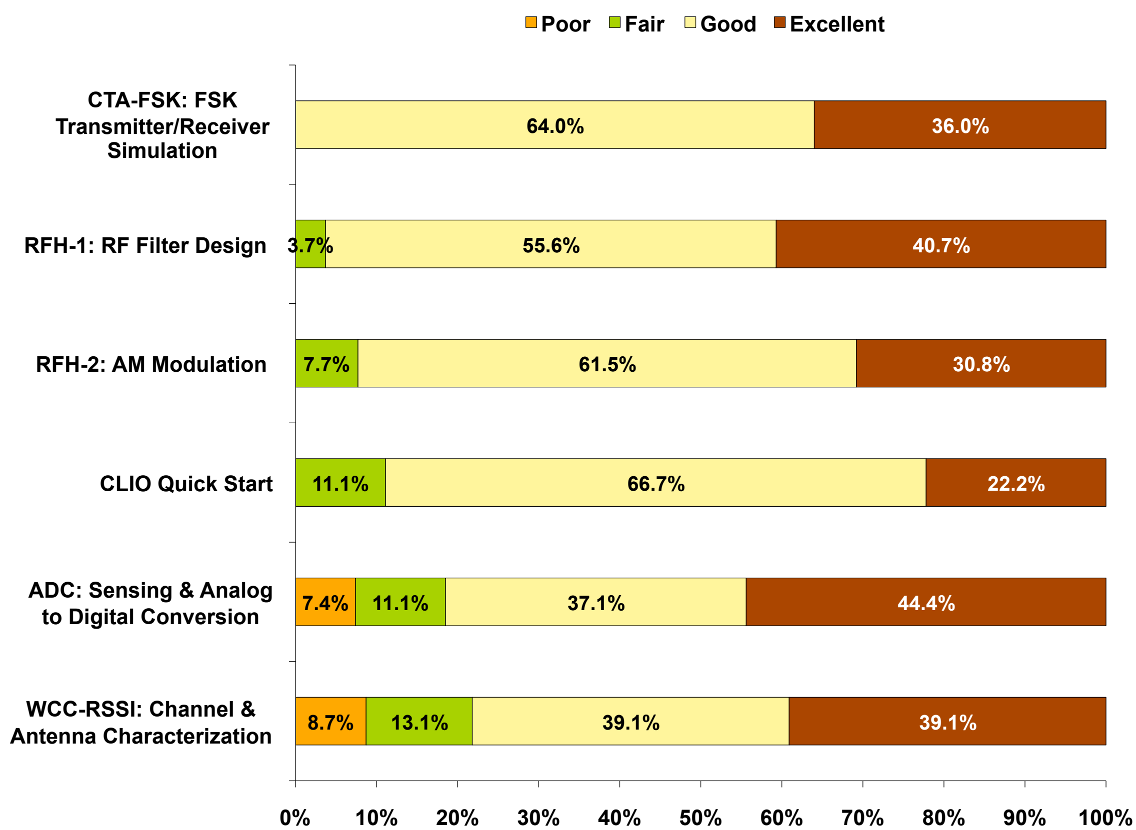

Figure 3. Student ratings of individual experiments.

During focus group interviews, students at both institutions commented that they enjoyed the experiments and that they enhanced their learning by giving them a way to apply the concepts from the modules to help them better understand key concepts in the course. Students mentioned that they particularly liked using Microwave Office. While they had used simulation tools before, Microwave Office was more generic than others they had used in the past and therefore could be used in many ways that would be helpful in future work including their capstone design courses.

There were differences in some aspects of student feedback at the two institutions that are worth noting. Students taking the course at Northern Arizona University had had prior experience with the C programming language from previous courses in their degree program. Many of the students at University of Vermont had not had similar experiences with C, and this was a point of difficulty for them with the experiments. Students commented that they did not feel prepared and that the first lab (CLIO Quick Start) was “a crash course in programming.” Students also commented that while they enjoy doing the labs, it took a lot of time for troubleshooting the programs and software. One commented, "you have to be motivated to learn all the software – if not, you’re just getting by and do it to get a grade.” Another said, “When I am done they are fun – a real big part is getting yourself ready to do the experiment, but actually doing the experiment is kind of small.” While several students saw the learning curve for languages and software to be a problem with the experiments, others noted that it was a good learning experience, and made the learning meaningful.

Overall, the experiments presented new challenges since they were complex in themselves. A good example is the experiment WCC-RSSI: Channel and Antenna Characterization (see Table 2), which required students to combine skill sets in new ways. It involved a procedure that required planning the experiment, programming the wireless nodes to establish a wireless link and exchange packets, gathering the RSSI data using two wireless transceivers, transmitting the data to a PC via serial communication, importing, analyzing, visualizing, and interpreting the (noisy) data, and inferring a parameter (the channel propagation loss exponent) using statistical tools. There was no “correct” answer, and the datasets were sometimes unpredictable, confusing or incomplete. Most of the experiments proved to be “messy” in this way; we contend this is good, since students learn how design and test work in real-world engineering.

Conclusion and Future Work

In this paper we have presented a series of hands on hardware- and simulation-based experiments designed to emphasize systems thinking as related to wireless sensor networks. The experiments assist in connecting normally disparate areas of electrical engineering and serve as a model for how complex engineered systems are developed and analyzed.

The materials were implemented and assessed at two universities in Fall 2009. Two additional universities are utilizing these materials in Spring 2010. The authors are actively looking for adopters for the online materials and the experiments discussed herein. Content is continually being revised based on student and faculty input.

Acknowledgements

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