AC 2007-1630: EXPERIMENT, EXPLORE, DESIGN: A SENSOR-BASED INTRODUCTORY ECE LABORATORY

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Experiment, Explore, Design:
A Sensor-based Introductory ECE Laboratory

Abstract

A new introductory course, *Fundamentals of Electrical and Computer Engineering* (ECE), has been designed to provide a rigorous, integrated introduction to the ECE field. The course laboratory, described in this paper, both promotes concept integration and provides a mechanism by which students can explore applications. Consistent with the curricular theme of Integrated Sensing and Information Processing (ISIP), a microcontroller-based robotic platform that includes a suite of sensors was selected as the foundation of all laboratory exercises. To develop both the students' conceptual understanding and their design skills, each laboratory session includes an initial, guided *experimental* component, in which basic concepts are investigated, and a subsequent open-ended *exploration* component, during which students are challenged to design a robot that completes a real-world task. After students complete a series of eight such laboratory sessions, the experience culminates in a five-week Integrated Design Challenge (IDC). To successfully complete the IDC, students have to go beyond the knowledge developed in previous weekly laboratory activities, assimilating new knowledge and using new sensors or processing data in new ways. The IDC is structured to not only emphasize technical accomplishments, but also to promote the development of project management, team organization, and communication skills.

This paper elaborates on the philosophy behind the design of the laboratory experience, describes specific laboratory activities (including the IDC), and provides an assessment of the course based on data from several semesters. These data indicate that the more integrative, design-oriented, sensor-based approach benefits students in a variety of ways such as reinforcing fundamental concepts, motivating the study of ECE, and providing an opportunity to develop creative problem solving skills. In addition, the laboratory experience has been shown to have a significant positive impact on the achievement of several ABET criteria.

1. Introduction

As part of broad curriculum reform, a new introductory course entitled *Fundamentals of Electrical and Computer Engineering* has been developed and established as the cornerstone of the ECE curriculum at Duke University. The *Fundamentals* course introduces core concepts that span all of ECE: how to interface with the physical world; how to transfer and transmit energy and information; and how to extract, analyze, and interpret information. These concepts are developed within the context of the curricular theme of Integrated Sensing and Information Processing (ISIP), introducing the framework that provides a roadmap for the remainder of the curriculum.

Key findings in engineering education literature have shown that both student interest and pedagogical effectiveness are increased when students have the opportunity to solve practical problems, particularly when those problems are presented within open-ended design challenges[1-5]. Thus, two primary curricular objectives of the *Fundamentals* course are to link theoretical concepts to real-world applications and to provide design experience early in the curriculum. Key to achieving these objectives is the laboratory experience, which occurs in weekly, 3-hour sessions that complement the twice-a-week, 75-minute lectures.

This paper describes the “Experiment, Explore, Design” approach used in the laboratory to challenge students to integrate and apply new knowledge in the service of realistic design problems. First, the overall philosophy of the approach is described, along with the key goals for each of the three components. Next, a set of specific examples are provided to illustrate how exercises have been implemented and how the laboratory differs from a traditional approach. Finally, assessment results are presented that indicate the success of the approach in improving student confidence and understanding, increasing student interest and motivation, and meeting several ABET criteria.

2. Laboratory Philosophy

Many introductory ECE courses include a hands-on laboratory experience. Most often, the constituent experiments consist of step-by-step progressions through exercises that enable students to observe or verify fundamental concepts. While this approach can be an effective method of teaching and reinforcing theoretical concepts, many students do not find it particularly motivating or insightful.

To promote concept integration throughout the semester, all *Fundamentals* laboratory exercises are based on a single platform. In selecting the platform, several criteria were critical. First, the ideal platform would enable the exploration of a broad range of ECE concepts. Second, this platform must be flexible to encourage the creativity inspired by open-ended problems. Third, the platform had to easily interact with its environment to facilitate the exploration and solution of real-world challenges. Finally, the platform must be easily connected to the ISIP curricular theme. The Parallax BASIC Stamp microcontroller and robotic platform meet these criteria. This platform has a broad variety of accessories (particularly sensors), yet remains simple to program and operate. These characteristics allow students to focus on the sensors and system design, rather than having to spend a disproportionate amount of their time programming the robot.

The laboratory experience for the *Fundamentals* course is organized into eight 1-week laboratory experiments, followed by a 5-week Integrated Design Challenge. The more traditional, guided experiment approach is still utilized in the 1-week laboratory sessions. However, these experiments are supplemented by exploration activities which provide students an opportunity to immediately apply the fundamental concepts that they have just investigated to solve a practical challenge. Gradually, over the course of the first eight weeks, the emphasis of the laboratory sessions shifts from guided experimentation to self-directed exploration. This evolution prepares students for the final test of their knowledge and skills: the Integrated Design Challenge.

2.1. Experiment

Our first goal is for students to verify fundamental theories and to validate key concepts through experimentation. We recognize that few of our students will have prior experience with – or even good intuitions about – experimental testing of ideas. Instead, they are more used to having key information given to them by their instructors. In our view, this makes it more important, not less, that the students learn basic engineering principles by a process of discovery. A key role of the instructors is that of a guide: they lead the students by indicating what observations need to be made, but the students collect the data themselves.

2.2. Explore

A second aspect of our philosophy is that laboratory activities should be open-ended, not fully specified, so that students ask their own questions. This emphasis has several advantages. Most notably, it requires students to take fundamental concepts from laboratory and find their practical uses. As they make such links, students will be increasingly motivated and excited by the laboratory, feeling a real sense of accomplishment. Furthermore, the students not only build something that works in each exercise, but they also develop specific skills (and learn about specific sensors within the ISIP theme) that increase their capabilities for solving the Integrated Design Challenge.

2.3. Design

Finally, we want to include real design problems in the laboratories. To solve problems effectively, students are challenged to integrate simpler components into a more complex project. Laboratory design projects also provide an opportunity for engineering students to develop non-technical skills: how to manage a complex project, how to cooperate with other students (and compete with other teams), and how to solve short-term problems while considering long-term goals and constraints. These skills are critical for success in real-world engineering environments.

3. Illustrative Examples

In this section, several laboratory experiments are described in detail in order to illustrate how the pedagogical philosophy and objectives discussed in Section 2 were implemented. The evolution from Experiment, to Exploration, to Design is also highlighted through these examples taken from the beginning (Laboratory #2), middle (Laboratory #5), and end (Integrated Design Challenge) of the semester.

3.1. Exploring Digital Logic: A Scrolling Display

Exploring Digital Logic is the second laboratory exercise that students perform. Students come to this laboratory session having been introduced to basic circuit variables and circuit elements (current, voltage, independent sources, and resistors), Ohm's Law, logic gates and functions, and logic function minimization and implementation.

In the context of the overall laboratory experience, the goals of this laboratory session include introducing students to the Parallax platform (microcontroller and PBASIC programming) and introducing them to a display device that could be generally used to convey information (e.g., about the state of the robot or a decision that had been made). Within this broader context, the laboratory exercises have specific goals related to the fundamental theories and concepts that have been introduced in the lecture. In service of these goals, after completing this laboratory exercise, students are expected to be able to:

- Construct and minimize two- and three-variable logic functions,

- Design, model, and build logic circuits with up to three input variables and seven output variables using a fixed number of TTL gates and,
- Design, model, and build logic circuits to drive a standard 7-segment display.

The Experimental section of this laboratory exercise begins with an introduction to the Digital Logic Trainer board (shown in Figure 1), on which students will construct their first project. Care is taken to describe each component and feature of the board: input devices (pushbutton, rocker switches), output devices (LEDs, speaker), the microcontroller and logic ICs, graphical depictions of various logic gates and how to relate the images to the actual electrical connections, and the breadboard workspace.

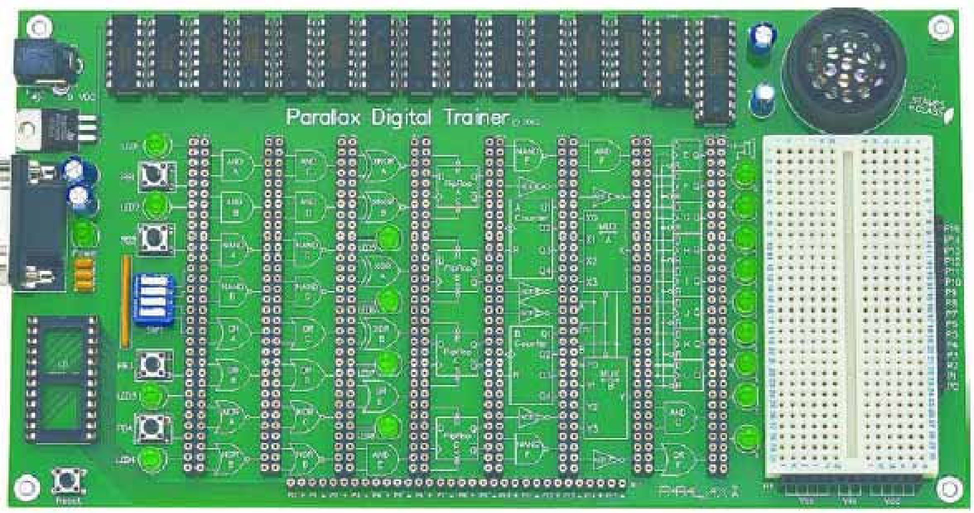

FIGURE 1. The Parallax Digital Logic Trainer board.

The first experimental activity is an investigation of basic logic gates: AND, OR, and NOT. By this time, students have a theoretical understanding of the operation of these gates, having derived truth tables in lecture. In this activity, students wire up pushbuttons to the input(s) of each gate and connect the output of the gate to an LED. Stepping through all possible input combinations, the truth table for each gate is verified. This not only reinforces the theoretical concepts, especially for those students who have a more sensory, active learning style, but introduces students to wiring and illustrates how a simple device such as an LED can be very useful in verifying circuit operation and in debugging a circuit.

In order to complete the Exploration component of this laboratory exercise (a scrolling 7-segment display), students must be able to use the microcontroller, rather than the pushbuttons, to control the gate inputs. Thus, in the next experiment, students build a simple counter (to scroll through the "frames" of the display) using the microcontroller. The microcontroller is programmed (using PBASIC) to toggle two LEDs to indicate the current (binary) count, starting with a one-bit counter (LED on or off) and followed by an expansion to a two-bit counter. As students do not yet have experience programming the microcontroller, the simple code is provided for them, along with a detailed explanation of each command. In this way, students are gradually introduced to various PBASIC commands so that eventually they are able to program the microcontroller independently.

At this point, students are familiar with the operation of the basic logic gates and have built a simple two-bit counter. The next step is to combine these fundamental pieces to implement a useful application: a scrolling 7-segment display. After being provided with some background on the functioning of a 7-segment display, students are guided through an exercise in which they build a circuit that scrolls the letters “E”, “C”, and “E” across the display. Throughout this part of the exercise, students are provided with significant guidance to aid them in learning how to approach the solution of a problem. However, later in the Exploration section, students are expected to extend what they have learned through this guided experiment to implement a related, but much more challenging project.

The first step in the problem is to derive the logic needed to display each character. Since there are four characters (“E”, “C”, “E”, and a blank space), the two-bit counter can be used to determine which character to display. In other words, the counter can be used to tell the display which of four “frames” to display. This observation immediately links the prior development of a counter to the current project goal. Next, it is necessary to derive the logic required to display a particular character in a given frame (i.e., which of the 7 segments should be on for each letter?). This leads to the derivation of the following table:

Frame	Character	P13	P12	A	B	C	D	E	F	G	H
0	E	0	0	1	0	0	1	1	1	1	0
1	C	0	1	1	0	0	1	1	1	0	0
2	E	1	0	1	0	0	1	1	1	1	0
3	space	1	1	0	0	0	0	0	0	0	0

Note that P13 and P12 are the output pins of the microcontroller (used in the two-bit counter) and the letters A-H correspond to the 7 segments of the 7-segment display. At this point, students have the opportunity to apply another theoretical concept introduced in lecture: logic function minimization, specifically using Karnaugh maps. Students are given a jump-start on this process by providing them with the maps for segments A through D (such as the one shown in Figure 2), but are expected to build the maps for the remaining segments on their own. This approach is in keeping with the philosophy behind the Experimental section of the laboratory exercise of providing students with significant guidance regarding implementation and observations to aid them in developing their problem solving skills, which student must then apply to a more open-ended challenge, with little guidance, in the Exploration section of the exercise.

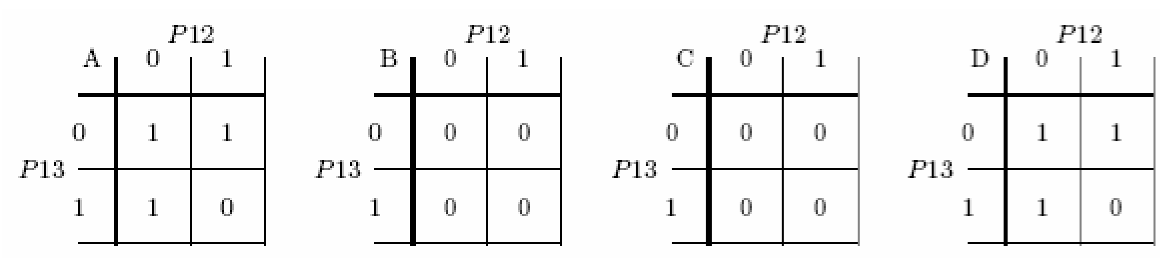

FIGURE 2. Karnaugh maps for segments A through D.

Students are told that the next step is to minimize the logic for each segment to derive eight logic functions. The result for one segment is provided to them. Armed with this set of functions, students are ready to build the scrolling display using the basic logic gates of the Digital Trainer Board and the two-bit counter which was previously built. In the end, students are rewarded with a scrolling display that demonstrates a practical application of many of the fundamental concepts of digital logic.

Having been guided through the solution to a two-bit counter-controlled scrolling display, students are asked to apply what they have learned to build a display that scrolls the word "robocoP" (or other seven-letter word of their choosing, provided there are sufficient gates on the Digital Logic Trainer board to implement). As "robocoP" requires six different characters (including a space) over eight frames, the two-bit counter must be extended to a three-bit counter. As before, a truth table, the logic for each segment, and the minimized functions must be derived and then implemented using the microcontroller and logic gates. As this is one of the first Exploration activities of the semester, this exercise is an extension of the Experimental activities to a more difficult version of the same application, rather than the use of fundamental concepts to solve an entirely new challenge, as is expected in later Explorations (such as the Tune Generator described in Section 3.2). However, in keeping with the overarching goals of the Exploration component, it does begin to establish the expectation that students will be able to apply the concepts and problem solving approach they have learned with relatively little guidance, provides a motivating practical application, and is open-ended enough that student creativity and curiosity are encouraged.

3.2. A Light-Controlled Tone Generator

By the time students reach the fifth laboratory exercise, A Light-Controlled Tone Generator, they have studied basic circuit devices and analysis, as well as digital logic. In the laboratory, they have progressed from implementing gate-level logic to drive LEDs and seven-segment displays (as described in Section 3.1), to building and testing systems that use input from a variety of sensors (e.g., temperature, pressure, and tactile sensors) to control the output response of the system (e.g., LEDs and seven-segment displays). Each week, the Experiment has focused on a set of fundamental concepts while the Exploration has strived to provide an opportunity for students to both apply new concepts and integrate all that has been learned previously.

The conceptual focus of the Light-Controlled Tone Generator is RC circuit design and analysis and time-varying signals. In addition, this laboratory exercise introduces students to a new sensor (a photoresistor) and a new output device (a piezoelectric speaker). After performing this laboratory exercise, students are able to:

- Explain what an RC time constant is and how it is determined in a circuit,
- Construct and perform a threshold detection using a photoresistor-based detection circuit,
- Explain how a piezoelectric device can be used to generate sounds, and
- Design a system which causes the BOE-Bot to respond to changes in light levels.

The Experimental section of this laboratory exercise begins with an investigation of the piezoelectric speaker. The speaker was used in previous laboratory sessions, but the device was treated as a black box and its functionality was not explored. With the introduction of sinusoidal signals and frequency in lecture, students now have the background needed to understand how the speaker operates. Students are introduced to a new PBASIC command which generates a sinusoidal signal and must determine the meaning of each parameter (Duration and Frequency) and write a program to generate tones of varying duration and frequency.

The second phase of the Experimental section involves the analysis of a series RC circuit. In lecture, a simple RC circuit has been analyzed and concepts such as the response to a time-varying signal and the time constant have been introduced and derived. Students choose a resistor and capacitor and calculate the theoretical value of the time constant for their series circuit. Using the function generator and oscilloscope (which were introduced in the previous laboratory session), a square wave signal is used as the input to the RC circuit and the oscilloscope is used to monitor and measure both the input voltage signal and the voltage across the capacitor. Students verify that the circuit input is a square wave and then observe that the output voltage (across the capacitor) is no longer square. Rather, the sharp edges have been replaced by an exponential rise and fall (as seen in Figure 3). Using the output waveform, students calculate the experimental value of the RC time constant and compare this to the theoretical valued computer earlier.

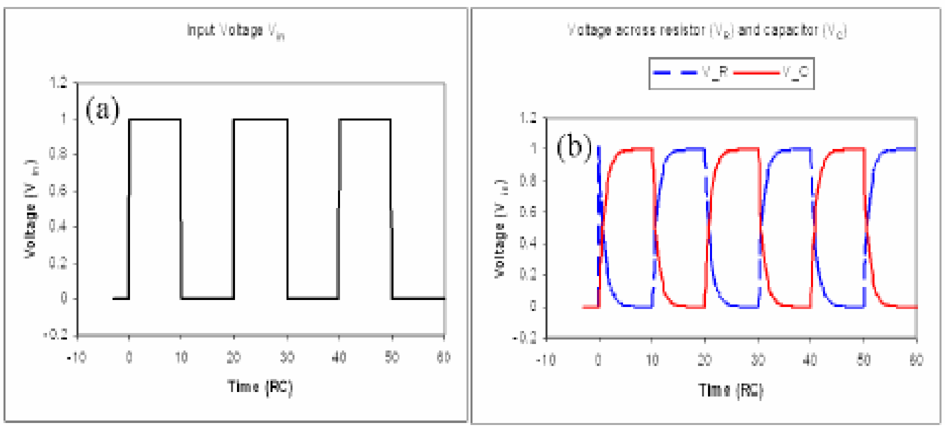

FIGURE 3. (a) Square wave input and (b) voltage across the series resistor (dashed line) and series capacitor (solid line), used as basis for measuring the RC time constant.

Students further explore the RC time constant and response of the circuit to a square wave by varying the frequency of the input signal. Students observe that as the frequency of the square wave increases, the maximum amplitude of the voltage across the capacitor decreases. However, the rate of rise and decay (i.e., the time constant) does not change. Although the concept of frequency response has not yet been introduced in class at this point in the semester, this exercise, couched in terms of the RC time constant and focused on time-domain waveform observations, provides a nice reference point and bridge to this topic when it is presented in the subsequent lecture.

The third area of experimentation in this laboratory session is the building and testing of a photoresistor circuit. To facilitate later integration of this sensor with the autonomous robot that will be built for the Integrated Design Challenge, the photoresistor is introduced in the context of robotic "eyes". Students first build a simple circuit with two resistors in series (a photoresistor followed by a fixed resistor), using the voltage measured across the fixed resistor as the input to the microcontroller. Students are reminded of the concept of voltage division introduced earlier in the semester and are asked to calculate the voltage across the fixed resistor in terms of R, the variable resistance of the photoresistor. Students combine this with their knowledge of the threshold voltage of the microcontroller's I/O pins and observe that as the light intensity varies (thereby changing the resistance of the photoresistor), the logic state of the I/O pin should be either 1 (when there is much light) or 0 (when little light is detected by the photoresistor). Using a piezospeaker which turns on and off depending on the state of the I/O pin, this theoretical observation is confirmed.

Students are led to observe one limitation of the previous circuit: the microcontroller can only determine if the light level is above or below a threshold. In the subsequent experiment, the circuit is modified by removing the fixed resistor and placing a capacitor in parallel with the photoresistor. The result is a circuit with a light level-dependent RC time constant. The I/O pin is set to measure the voltage across the capacitor. However, a new command is introduced, RCTIME, which measures the RC decay time of a circuit by applying a high (5V) voltage to charge the capacitor, then measures the time it takes for the voltage to decay to the threshold voltage (1.4V). Since the resistance of the photoresistor, and therefore the RC time constant, varies with light level, it is now possible for the microcontroller to know more about the light level in its environment, going beyond the binary states of greater than or less than a threshold.

Having experimented with the piezospeaker, a photoresistor, and RC series and parallel circuits, the students are prepared to embark on the Exploration component of this laboratory exercise. In contrast to the Scrolling Display Exploration (described in Section 3.1), this Exploration requires students to tackle a challenge that is more than just a more difficult version of the Experiment. In this Exploration, students are challenged to build a BOE-Bot that "sings". Moving one step closer to the open-endedness of the Integrated Design Challenge, the only information provided to the students is the following set of design specifications:

- The frequency of the tone generated by the speaker should be proportional to the intensity of light.
- The frequency of the tone generated by the speaker should not exceed 3000 Hz.
- The system should be designed such that the entire range of frequencies from 0 to 3000 Hz is generated as the intensity of light is varied.

Although the students have all the building blocks needed to complete the project, they quickly realize the importance of carefully interpreting design specifications and the challenges of system integration.

3.3. The Integrated Design Challenge: Mission Possible (Spring 2006)

The laboratory experience culminates in a 5-week design project, called the Integrated Design Challenge (IDC). Over the preceding eight laboratory sessions, student have experimented, verified, and explored a new set of fundamental concepts each week. In each session, new sensors and I/O devices have been introduced in the context of these concepts. Students have developed the skills needed to identify and define a problem and the technical knowledge (circuit design and analysis, programming, debugging and troubleshooting) needed to tackle a more challenging problem.

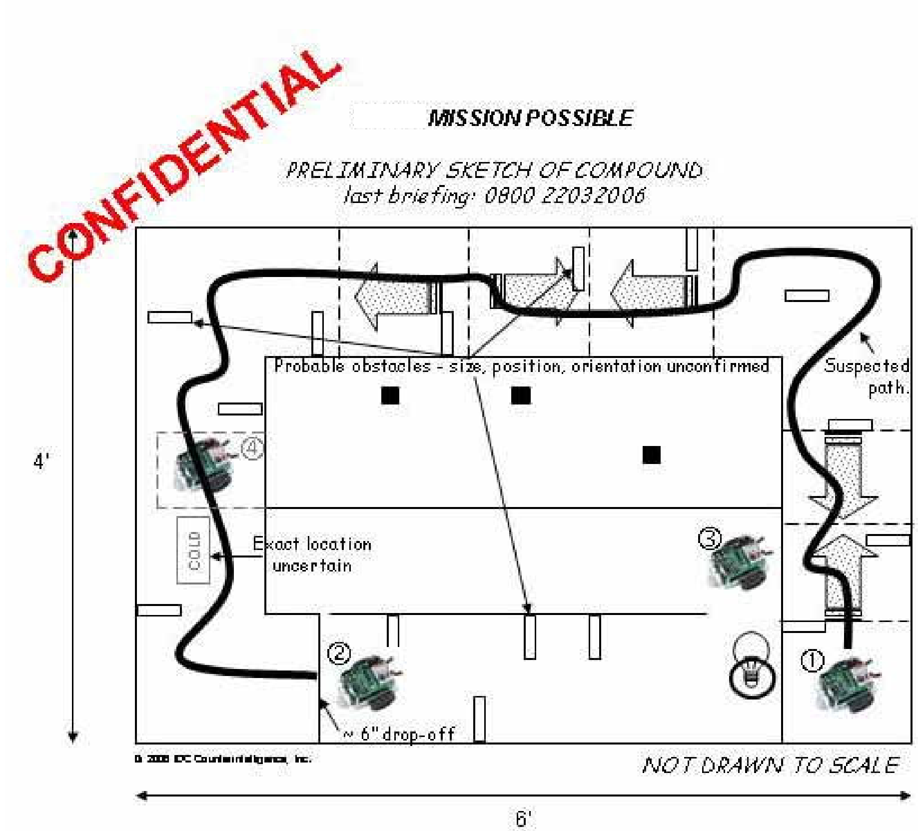

FIGURE 4. Preliminary intelligence provided to student teams for the IDC.

The theme of the Spring 2006 IDC was “Mission Possible”. Students were informed on the first day of the IDC that the school mascot had been kidnapped. They were provided with preliminary intelligence (i.e., problem specification and constraints) that described the “compound” in which the mascot was being held and the various obstacles that had to be overcome to safely rescue the mascot (see Figure 4). Students were surveyed prior to the start of the IDC to determine their strengths, weaknesses, and particular interests to aid the instructor in forming balanced sub-teams (of 2 to 3 students) within each laboratory group.

The mission had four phases, to be sequentially completed by different robots, each requiring a different set of sensors. Between phases, the robots had to communicate to indicate the successful completion of one phase and signal the initiation of the next. Each phase was designed so that there were multiple solutions, although in some cases, a particular solution may have been better than all other alternatives. The phases were:

1. **Perimeter Scouting.** In Phase 1, the robot had to follow a black line on a white background for approximately 15 feet around fixed obstacles, up and down hills, and around sharp turns, stopping at the edge of a cliff. To solve the challenges of this phase, students used IR emitter/detector pairs, in various configurations.
2. **Disabling the Perimeter Security System.** In Phase 2, the robot had to navigate approximately 5 feet down a narrow hallway strewn with obstacles to locate and turn off a bright incandescent light. Solutions to this problem included the use of tactile sensors (whiskers), photoresistors, and IR sensors.

3. **Opening the Internal Vault.** Once the security system of Phase 2 had been disabled, the robot in Phase 3 had to locate the switch to open the internal vault, which was known to be located in the coldest part of the room at the end of a 5 foot hallway. To accomplish this task, students used photoresistors, tactile sensors, an LCD display, LEDs, and Bluetooth communication.
4. **Locating the Hidden Mascot.** The fourth robot had to locate the mascot, which was hidden in a magnetized trunk somewhere in a room measuring approximately 1.5' by 5' and avoid selecting the decoy (un-magnetized) trunk. Teams solved this problem using magnets, a compass, IR sensors, and Bluetooth communication.

In addition to further developing the students' technical skills through individual robot design, inter-robot communication, and system integration, one goal of the IDC is for students to develop project management and communication skills. Thus, a variety of deliverables were required over the course of the IDC including:

1. **Conceptual Design Written Report (Due in week 1).** To emphasize the importance of planning in the design process, each sub-team was required to present a conceptual design to the instructor before they were allowed to begin actual construction of their robot. This report included:
    a. the problem statement in the students' own words,
    b. a list of objectives and deliverables,
    c. a schedule with important milestones and task assignments (Gantt chart), and
    d. a discussion of the requirements, constraints, alternatives considered, and justification for the proposed design.
2. **Preliminary Design Oral Presentation (Due in week 2).** At the end of the second week, each sub-team had to present a status report indicating the progress they had made, challenges they had run in to in their design, and risks to successful completion of the project. Prototypes could also be demonstrated. In addition to feedback on their technical progress, students' oral communication and presentation skills (including Questions and Answers) and team functioning were assessed.
3. **Individual and Team Robot Demonstrations (Due in weeks 3 and 4).** The next two weeks were devoted to refinement of design, construction, and testing of the robots.
4. **Final Competition (Due in week 5).** At the end of the fifth week, the final competition between the two laboratory sections was held in public.
5. **Final Written Report (Due in week 5).** The final technical report was comprehensive, including the conceptual design and design considerations, the technical details (with documentation of hardware and software) of the solution implemented by the team, and an analysis of the successes and failures of the design.
6. **Final Oral Presentation (Due in week 5).** As a team, the lab section made a final presentation following the final competition. Students were evaluated primarily on their skill in handling questions and in working as a team to produce a coherent oral presentation.
7. **Budget and Timeline reports (Due weekly).** Each week, every group submitted an updated budget for their design, as well as a current Gantt chart indicating progress.

4. Assessment

The impact of the “Experiment, Explore, Design” approach to the laboratory experience in the new *Fundamentals* course was evaluated both in absolute terms and relative to the traditional introductory course, *Introduction to Electric Circuits*. The technique used for evaluation was the student survey, of which two types were administered: post-laboratory and post-course. Data from these surveys were also compared to normative data from previous offerings of the *Introduction to Electric Circuits* course.

Students (N_{S06} = 19; N_{F06} = 39) were surveyed anonymously following each laboratory session and at the end of the semester. The end-of-semester survey requested student feedback regarding the extent to which the laboratory experience overall 1) contributed to their understanding of the course material, 2) increased their interest in the course material, 3) was well-integrated with the lectures, and 4) enabled them to think critically about course material. Individual end-of-session surveys queried students as to the degree to which a particular laboratory exercise illustrated 1) a real-world/practical application of theoretical concepts and 2) the ISIP curricular theme. The results of these surveys (percentage of respondents who gave each answer) are presented in Table I. Data for the first four questions were obtained from the end-of-semester survey (N = 41); the data for the fifth and sixth questions represent a weighted average compiled from all end-of-laboratory session surveys (N = 285).

TABLE I. Assessment of laboratory experience: Percentage of student responses on end-of-semester survey (Q1-4, N = 41) and end-of-session surveys (Q5-6, weighted average of N = 285).

Question	**SD**	**D**	**N**	**A**	**SA**
Q1: Overall, this laboratory contributed to my **knowledge of the subject**.	1.8	0.0	9.0	40.3	48.9
Q2: Overall, this laboratory increased my **interest in the subject**.	4.2	5.4	10.8	21.7	57.9
Q3: The concepts and skills taught in laboratory were **well integrated** with those taught in class.	7.8	5.4	18.0	41.6	27.2
Q4: This laboratory helped me **think critically** about course material.	2.4	9.0	16.2	34.9	37.5
Q5: This laboratory exercise illustrated a **real-world/practical application** of theoretical concepts.	0.3	3.0	9.7	55.6	31.3
Q6: This laboratory exercise was clearly **related to the curricular (ISIP) theme.**	0.3	0.9	10.8	60.8	27.2

SD = Strongly Disagree, D = Disagree, N = Neither Agree nor Disagree, A = Agree, SA = Strongly Agree

The majority of students felt that the laboratory as a whole contributed to their conceptual understanding and interest in the course material. In addition, most students also perceived that the laboratory was well-integrated with the more theoretical view presented in lecture which enabled them to think more deeply about the topics. Such positive results suggest high student engagement in the course and significant learning enhancement taking place in the laboratory. Furthermore, the high percentage of agreement that the course illustrates real-world applications and is strongly tied to the Integrated Sensing and Information Processing (ISIP) curricular theme signifies that this laboratory approach provides the desired motivation and thematic basis on which to build in subsequent courses.

In addition to the student survey data presented above, a second comparative assessment was conducted to assess the impact of the “Experiment, Explore, Design” approach. For this evaluation, data collected from students enrolled in the *Fundamentals* course was compared to data collected from students who had taken the more traditional *Introduction to Electric Circuits* course. As part of standard course assessment activities, the students are asked to rate, on end-of-semester surveys, the degree to which they felt a course met specific Accreditation Board for Engineering and Technology (ABET) criteria (listed in Table II). The data collected from students in three semesters of *Electric Circuits* (N = 58) was compared to data from two semesters of the *Fundamentals* course (N = 48). Because these students differed in several factors, a regression analysis was conducted. Three factors were included as predictor variables: course (the factor of interest), instructor, and semester. Student responses on the eleven ABET criteria were used as dependent variables, using each student's numerical response to each question (from "1: Strongly Disagree", through "5: Strongly Agree"). The regression analysis examined whether each of the three predictor factors made an independent contribution to the students' ABET responses; i.e., whether the *Fundamentals* course made students more likely to agree with a given criterion, even while controlling which instructor was teaching the course and what semester the course was being taught. Because 33 separate statistical tests (3 predictors by 11 criteria) were conducted in this regression, the needed probability value to reach significance was determined to be $0.05/33 \approx 0.0015$.

The more design-focused approach was expected to be a more effective method for both improving student understanding and motivation and for developing important skills such as problem solving and teamwork. The regression analysis (see Table II) revealed that the *Fundamentals* course was judged significantly better on three of the ABET criteria: "Design and conduct experiments, and analyze and interpret data", "Design a system, component, or process to meet desired needs", and "Function on a team" (all at a probability level, p, of ≤ 0.0015). None of the three factors for any other question met the threshold for significance. This result indicates that these three ABET criteria can be directly related to the design experience in the *Fundamentals* course, while more general criteria (e.g., "Apply knowledge of math, science, and engineering") showed no significant difference between courses. Furthermore, the selective results of the regression analysis eliminate the possibility that *Fundamentals* students simply were more generous in their ratings than students in the other courses.

TABLE II. Assessment results for ABET criteria: p-values of regression factors.

ABET Criteria	**Semester**	**Course**	**Instructor**
a) Apply knowledge of math, science, and engineering	0.18	0.01	0.72
b) Design and conduct experiments, and analyze and interpret data	0.12	**0.00013**	0.58
c) Design a system, component, or process to meet desired needs	0.75	**< 1e-6**	0.08
d) Function on a team	0.86	**0.00015**	0.97
e) Identify, formulate, and solve engineering problems	0.81	0.0026	0.78
f) Understand professional and ethical responsibility	0.22	0.47	0.27
g) Communicate persuasively, in writing and orally	0.54	0.04	0.85
h) Understand the impact of engineering solutions in global and societal context	0.10	0.21	0.91
i) Recognize the need for engaging in life-long learning	0.72	0.92	0.75
j) Know and understand contemporary issues	0.76	0.48	0.64
k) Use techniques, skills, and modern engineering tools necessary for engineering practice	0.0021	0.0053	0.10

5. Conclusions

The laboratory for the new introductory *Fundamentals of ECE* course has been designed to provide a link between theory and practical applications and to develop a broad set of skills through an approach emphasizing experimentation, exploration, and design. The success of this laboratory is due, in part, to the use of sensors to facilitate the presentation of basic concepts in a realistic framework. By challenging students to complete guided experiments and solve open-ended problems, this laboratory serves to both reinforce fundamental concepts and motivate their study. Based on assessment results from the first two offerings of *Fundamentals*, there is strong evidence that the "Experiment, Explore, Design" approach effectively improves student understanding, motivation, and design skills.

Bibliography

1. L. J. Shuman *et al.*, "The future of engineering education," in *Proc. 32nd Annual Frontiers in Education Conference*, 2002.
2. B. Olds and R. Miller, "The effect of a first-year integrated engineering curriculum on graduation rates and student satisfaction: A longitudinal study," *J. Engineering Education*, pp. 23–36, Jan. 2004.
3. J. H. McLellan *et al.*, "Using multimedia to teach the theory of digital multimedia signals," *IEEE Trans. Education*, pp. 336–341, Aug. 1996.
4. C. C. Munson, "Elements of a new Electrical Engineering curriculum at Illinois: A shift from circuits to signal processing," in *Proc. 1995 IEEE Symp. Circuits and Systems*, vol. 2, 1995, pp. 1–4Sf.
5. B. Masi, "The impact of faculty-mentored versus web-guided engineering design experience on freshman skills," in *Proc. 2003 Annual Conference of the American Society of Engineering Education*, 2003.