ASEE 2014 Zone I Conference, April 3-5, 2014, University of Bridgeport, Bridgpeort, CT, USA.

Incorporating a substantive hands-on experience into the Intro-to-EE course for non-majors

A.M. Annan, C. M. McLain, M. E. Perham, D. N. Robear, and D. J. McLaughlin
Dept. of Mechanical & Industrial Engineering, Dept. of Electrical & Computer Engineering
University of Massachusetts
Amherst, MA

***Abstract*—Obtaining hands-on experience with an engineered system is an effective way to reinforce and motivate the learning of fundamental concepts during undergraduate engineering education. We describe recent experience at the University of Massachusetts in introducing a laboratory component into the Fundamentals of Electrical Engineering course taken by 170 upper-level mechanical and industrial engineering undergraduate students. The lecture part of the course exposes students to linear circuit and system theory, digital logic design, and electronics. The piloted lab component ran in parallel with the lecture component. In the lab component, students were arranged into teams, assigned an experiment-kit, and charged with designing, building, testing, operating and demonstrating collision-avoiding robotic "smart cars." Subjective assessment indicates that students were highly satisfied with the experience, and many are motivated to do more with electronics. This paper summarizes this experience, provides lessons-learned, and describes next-steps in the evolution of this course**

I. Introduction

A one-semester course introducing the fundamentals of Electrical Engineering to mechanical, industrial, and other non-EE majors is a typical component of today's baccalaureate engineering curriculum. The version of this course at the University of Massachusetts Amherst, ECE361, is required for junior-level mechanical engineering majors and senior-level industrial engineering majors. Recent enrollment exceeds 175 students in the course, which runs during the fall semester of each year. Topics include linear circuit and system analysis, digital logic, transistors and diodes, and electromechanical devices. The formal prerequisites for the course include differential equations and an undergraduate physics course with an electromagnetics lab component. One of the stated objectives of the course is "to provide the non-EE student with relevant EE concepts & device knowledge to effectively work in multi-disciplinary design, development, & manufacturing teams." Historically, the course has been lecture-only. Since it can be a difficult, and sometimes abstract, course that students are required to take in an area that they perceive as being outside their major, the student cohort tends to experience the course with a variety of attitudes and overall satisfaction. During the Fall of 2013 we conducted a pilot experiment in which we introduced a substantive hands-on component into the course. There were several motives for doing this. First, contemporary thinking about engineering education points to hands-on experiences as a necessary ingredient in the learning process. A participant in the recent 2013 ASEE University/Industry perspectives workshop stated this succinctly, "Students must experience a hands-on example of every fundamental taught in order to reinforce it. Without reinforcement, most fundamentals are never digested by the students" [1]. Second, there is the sense that engineering students are missing out on some of the excitement associated with "hooking things up" and "making things" in a way that leverages electrical engineering knowledge. We have witnessed a dramatic nationwide decrease in undergraduate electrical engineering enrollment over the past decade (down 24% from 2000 – 2009) at the same time we have seen a corresponding increase in mechanical engineering enrollment (up 36% over the same period) [2]. There has been an uptick in electrical engineering enrollment in recent years, but it remains the case that student interest in electrical engineering is not what it might be - or perhaps should be - considering all the ways that electrical engineers impact technology, the economy, and our quality of life. The reasons for these trends are not entirely known, but informal discussions with undergraduate mechanical engineering students suggests that many students are choosing that major because they associate mechanical engineering with automobiles, mechanisms, robotics, spacecraft, energy, and other tangible, hands-on and accessible system themes. Based on these observations, we decided to introduce a hands-on component into ECE361 that would combine elements of cars, gears, motors, and systems, with electrical engineering elements including transistors, integrated circuits, embedded microcontrollers, power-switching devices, LED's, etc… Our hypothesis was that a hands-on component would help to reinforce learning of the fundamentals; provide a context for students to work in groups on iterative design/building/testing; and positively impact the students' enthusiasm and overall satisfaction with the Fundamentals of EE for non-majors course.

II. Approach

Introducing a lab component to a course, particularly one involving 175 students, obviously presents a logistical challenge. Laboratory space is one of the most precious, and potentially contentious, resource management issues in academia today, and prospects are low for finding new dedicated space for such a large group of students. The approach taken here was to distribute self-contained experiment-kits to groups of four students. The students owned the kits, took them home, shared them amongst their team, and worked on a set of experiments asynchronously throughout the semester, culminating in the design, test, and demonstration of a collision-avoiding vehicle. Figure 1 shows a group of students working with their kit. The UMass Department of Mechanical and Industrial Engineering's Innovation Shop was then made available to students 24/7 as a drop-in maker space where they found lab benches, test equipment, expert assistance, and other teams working on similar problems. With this approach, we aimed to have the students undertake substantive hands-on learning and design activities, culminating in a collision-avoiding car that they would build from scratch, without requiring any dedicated lab space or equipment.

With a high-level statement-of-work, a set of incremental asynchronous lab assignments, and a shared take-home experiment kit, a large class of 170+ mechanical and industrial engineering students can successfully team-develop small autonomous cars, from scratch, enhancing their motivation while reinforcing their learning of electrical engineering fundamentals.

Summary elements of the new hands-on component of ECE361:

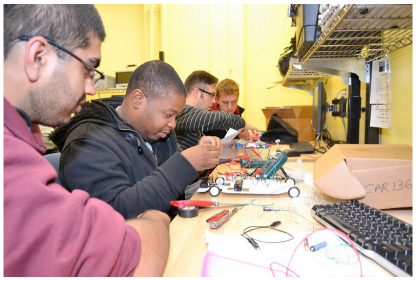
- A hallmark of the course was a pair of major deliverables: students were required to design, build, test, and demonstrate a small, autonomous, obstacle avoiding "smart car". They were told of this on the first day of class. They worked through a series of labs dealing with various aspects of the car, described below, in a way that complemented the fundamentals being taught in lecture. These labs then culminated in major deliverables associated with autonomous functioning of their smart cars.
- All 175 students taking the course participated through lab teams of four; they entered the course with no prior EE background other than E&M physics and differential equations.
- All lab teams were able to successfully build and demonstrate a functional smart car from scratch.
- The experiment kit assigned to students contained wire cutters, digital multimeter, breadboards, an Arduino UNO microcontroller, wheels, axles, and gears; a small DC motor; an Arduino-compatible micro-servo and sonar sensor, and an assortment of electronic components including Op Amp, 555 timer, logic gates, transistors, resistors, capacitors, LED's, and batteries.
- A half-time graduate teaching assistant staffed a drop-in lab clinic in the maker space 2 times weekly.

End-of-semester student course evaluations show very high satisfaction with the course and the subject matter. "Overall course rating" achieved a score of 4.7 out of 5.0 (standard deviation 0.6) when averaged across the 175 participants in the course. This compares to a college-of-engineering-wide average of 3.5 (standard deviation 0.5) and campus-wide average of 3.7 (standard deviation 0.5). The student survey mechanism did not provide the means to separate out the hands-on component from the lecture components of the course, but the overall assessment and a substantive volume of student comments clearly point to a very high degree of satisfaction with the hands-on component of the course.

A car-demo "rally" was held in the auditorium of the UMass campus center on the last day of classes. During this rally, all 40+ student teams had the opportunity to showcase, race, and participate in a "collision-avoidance derby" with their smart cars. A youtube video of this event can be seen at https://www.youtube.com/watch?v=1tJwOuOdzlQ.

After completing a pilot semester, it is evident that the hands-on component is adding value to the student experience of this Fundamentals of EE course. In order to move beyond the pilot, or trial version, a group of student participants from the course (the first four authors of this paper) was retained by the course instructor, Prof. McLaughlin, as winter-term Research Experience for Undergraduate (REU) research assistants. This team was charged with conducting a re-design of the lab experiments and a re-design of the experiment-kit for the course. The experiment-kit redesign is particularly important since in the future it will be necessary to create up to 100 of these kits every year. The re-design of the labs sought to uncover the reasons behind several recurring component failures and problems that were encountered during the course. The re-design of the experiment kit emphasized selecting reliable components and vendors, packaging, and cost for a kit that can be replicated as needed in future. The following sections of this paper summarize the lab experiments, key lessons learned, and important design changes for going forward.

Figure 1. Students working with their kit



III. LAB EXPERIMENT SUMMARY

ECE 361 took place over a standard 14-week semester. Students were nominally formed into teams of four, although there were a few groups of three and five. The teams were instructed to complete seven lab assignments (approximately one due every other week) and two major demonstrations, summarized in Table 1. The major demonstrations addressed the functionality of a smart car that was to be built from scratch using the wheels, motor, transistors, Arduino UNO microcontroller, batteries, etc… from the kit. The individual lab assignments dealt with smaller circuit elements (eg, op amp comparator circuit; H-bridge circuit; transistor current amplifier to drive a motor); or hardware module (Arduino-compatible micro-servo or sonar sensor) or software (specifically, Arduino scripting) subsystems that would typically be needed to achieve the system-level deliverable. The individual assignments thus helped to reinforce the learning that was taking place as theoretical elements were introduced during the lectures and homework assignments, while the system-level deliverable exposed the students to some of the complexity of systems engineering. The pedagogical approach behind this design follows contemporary thinking about the undergraduate engineering curriculum, such as articulated in the NAE 2020 report, which advises, "Whatever other creative approaches are taken in the four-year engineering curriculum, the essence of engineering – the iterative process of designing, predicting performance, building, and testing – should be taught from the earliest stages of the curriculum…" [3]. The system-level deliverable required the students to undertake a more open-ended problem solving approach to realize a functioning "smart car" that was capable or autonomously moving forward or backward when it detected obstacles or different levels of light in the room. This approach, which combined well-structured weekly labs with more open-ended semester-long demo deliverables, is consistent with the thinking articulated in the Carnegie Foundation's recent text on engineering education, which is aimed at developing a student's perspective to complement a student's technical depth. That text notes, "When the teacher's goal is helping students to deal with complex engineering systems, the prevalent model of instruction is focused on developing the students' capacity to negotiate the laboratory components and deal with the unexpected…The instructor presents the problem and provides minimal guidance, as students take the lead in the investigation. They determine which theories to use and what physical evidence must be considered or ignored. Because of the problem's complexity, students are encouraged to think critically and make judgments. Although students may often encounter failure in these open-ended, minimally-structured experiments, they eventually see it as part of the process of the investigation, during which they are expected to analyze, synthesize, and evaluate concepts learned as they apply them to complex engineered systems. Since more open-ended laboratory experiments integrate materials from various engineering disciplines, they provide an environment that approximates engineering practice" [4].

Each lab was assigned at least a week before its due date and each group was required to upload a picture/video of the circuit to the course Moodle site to demonstrate functionality.
Drop-in help clinics, run by an EE graduate teaching assistant, were also offered in the Innovation Lab (MIE work space) prior to lab due dates. Students who attended could receive help from the graduate TA (teaching assistant) or occasionally from the professor responsible for the course; this encouraged student collaboration and provided helpful instruction in troubleshooting to the student teams. Figures 2 and 3 show representative photographs of student circuits. Figures 4 and 5 show examples of smart cars that were demonstrated at the end of the semester.

FIGURE 2. Student-built state-machine

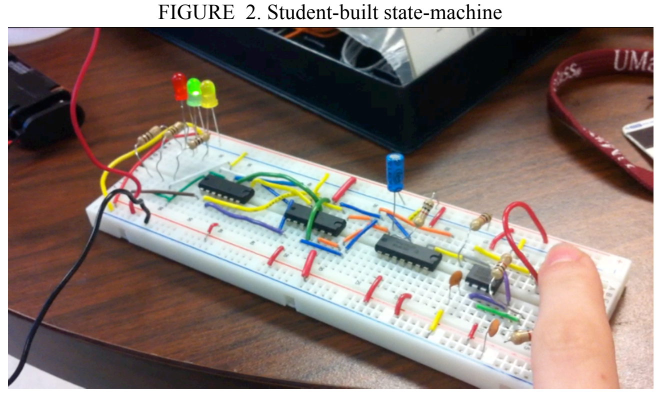


FIGURE 3. Light-detecting alarm circuit

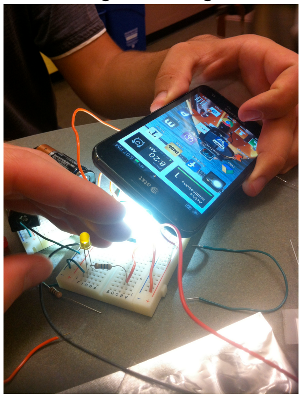


FIGURE 4. Example student smart-cars

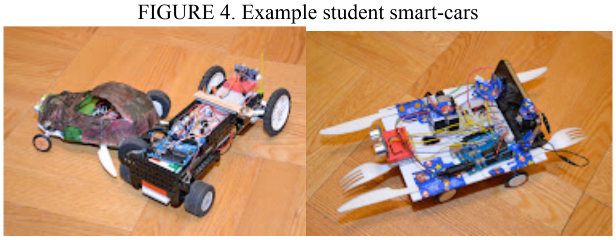


FIGURE 5. Student testing their smart-car

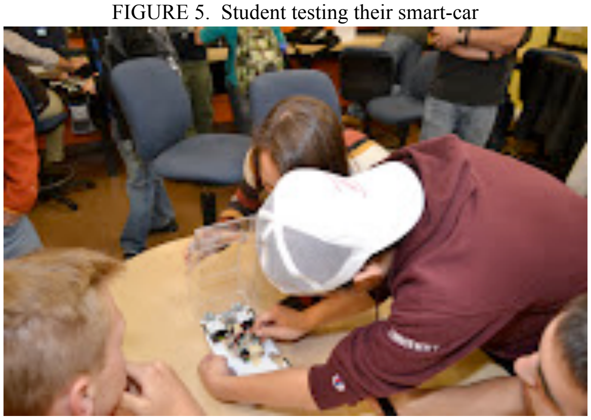


TABLE I. INCREMENTAL LAB AND MAJOR DEMONSTRATION ASSIGNMENTS

Assignment / Lab	***Topic***	***Deliverable***
Lab I	Kit inventory	
Lab II	Light Sensitive Resistor Op-Amp comparator Voltage divider Cadmium Sulfide Cell	Light detecting alarm
Lab III	Op Amp comparator Transistor as current driver DC Motor	Incorporate transistor current amplifier into the light-detecting alarm to drive the motor based on ambient light level.
Lab IV	Digital State Machine. Integrated Circuit exposure. Switch debouncing Power-on reset	Digital logic circuit that sequences through light states with subsequent push of a button
	H-bridge testing using discrete power transistors	
Car Demo I	Build car chassis including mechanical drive; integrate with electronics from previous labs	Car moves forward in the presence of ambient light but moves backward when a strong flashlight is shown onto the car from above.
Lab V	Arduino UNO operation and IDE experimentation	Download Arduino IDE and perform some basic tasks to become acquainted with software and use
Lab VI	555 timer circuit; Arduino-controlled sensor and alarm	From lab 3, replace Op Amp with Arduino and LED with a piezo speaker
Lab VII	Ultrasonic sensor for obstacle detection and distance measurement.	Incorporate ultrasound sensor into Arduino alarm subsystem.
Car Demo II	Build car chassis including mechanical drive; integrate with electronics from previous labs.	Demonstrate a car that moves forward in the presence of ambient light but moves backward when a strong flashlight is shown onto the car from above.

IV. IMPROVEMENTS AND KEY LESSONS LEARNED

There are many indications that having four students per team, with one lab kit and one set of deliverables per team, is too crowded. In many cases, having four students share the kit denies access to the parts to some students, particularly those who are less experienced or less dominant. In the re-design for the next iteration of this course, kits will be assigned to *pairs of students* and the first three lab assignments will be completed by student pairs. The pairs will then have the option to join with another pair to complete the subsequent labs, and the major demos if they wish. This change essentially doubles the amount of hardware and parts available to the students, and helps insure that all students acquire hands-on experience, while at the same time allowing collaboration. This also helps to mitigate the dilemma of having an uneven distribution of effort among teams of four if one or multiple members rely on others to do the majority of required work.

In the re-design of the lab student teams will still be required to submit photographs or videos of their lab circuits to the Moodle course site to prove functionality, however, additional questions, specific to each lab, will need to be answered *by each student* and included in the submission. We believe this is a good way to reinforce each student's individual understanding of key lab concepts even if they didn't get a chance to be heavily involved with the group completion of the project.

Battery drain was a constant issue during the first run of the course. Students used combinations of AAA batteries, AA batteries, and 9-volt batteries. The 9-volt batteries were used predominantly to power the Arduino UNO microcontroller board, and the other batteries were used to drive motors. The Arduino UNO is capable of operating with an input voltage between 5.5 and 9 volts; this device has an on-board voltage regulator that produces 5 volts output and is used to drive servo motors, ultrasonic sensors, and other devices. It was consistently found that 9-volt batteries drained too quickly, resulting in an assortment of problems downstream. In subsequent versions of the course, students will be instructed to use AA batteries exclusively.

H-bridges were used to provide forward/reverse operation of the DC motor, but students experienced frequent H-bridge failure in their cars. The solution to this is to use only H-bridges with internal diodes to prevent back EMF voltage spikes, particularly when Pulse Width Modulation (PWM) is implemented to vary motor speed. Subsequent experiment kits will provide the students with an L293DE H-bridge IC chip containing internal diodes.

A seemingly mundane item, the box that houses the parts in the experiment kit, serves important functional and aesthetic roles. In the first distribution of the kits, the components were distributed in a 11x 8 x 4 inch box made of corrugated cardboard with a matte surface. This size fit all the pieces, the organizational tools, and allowed space for the semi-completed labs, as well as for the final car to be carried. However, this size box introduced carrying limitations since it had no handle and could not fit into typical sized student backpacks. A search is currently underway for a replacement box that has similar or smaller dimensions, but also has a carrying handle, preferably on top of the box to minimize jostling of parts between carrying and opening. A more durable and more weather-resistant box made of plastic is also being considered, but the durability needs to be traded against the increased cost of the kit. The cost issue is addressed further below.

A 12" x 18" sheet of corrugated plastic was included with the experiment kit during the first run of the course and students were encouraged to use this sheet to build the car chassis. While many student teams followed this advice, many other teams approached the chassis differently, including mounting the circuitry on a Monster RC Truck. In consideration of the excellent range of innovation that is apparent in these figures, the decision has been taken not to include the corrugated sheet as the default chassis going forward. This material will be stocked and supplied at the request of student teams, but they will be encouraged to be creative, especially with the mechanical aspects of the design, when approaching the realization of their car chassis. The revised experiment kit will include the items listed in Table 2.

TABLE 2. REVISED EXPERIMENT KIT INVENTORY

Item	***Quantity***
Wirestripper	1
Wire assortment set (multi-color)	6 ft
Digital Multimeter	1
AA Batteries	
3 volt plastic battery holder	1
6 volt plastic battery holder	1
Servo motor	1
DC mini motor	1
Motor bracket housing	1
Four wheel set with axle and gears	1
Arduino microcontroller with USB	1
Ultrasonic Sensor	1
Large breadboard	1
Small breadboard	1
Red LED	2
Green LED	2
Yellow LED	2
0.1 microfarad capacitor	2
10 microcapacitor	2
PNP power transistor	2
NPN power transistor	2
NPN signal transistor	1
H-Bridge integrated circuit	1
555 timer integrated circuit	1
AND gate integrated circuit	1
FLIP-FLOP integrated circuit	2
Tactile contact switch	1
Two-stop slide switch	1
Resistor	
Organizational tool boxes	2
Durable material kit box	1

V. Experiment Kit Costs, Distribution, and Ongoing Support

The re-designed experiment kit will cost ~ $90, not including batteries. When batteries and a durable box are included, it is expected that the kits will cost $110, which equates to $55 per student when considering one kit per two students. At this point, our plan is to keep sufficient supply of parts in inventory so that during the summer months, we can assemble the ~100 kits needed for the fall semester. The assembly and distribution will be done by the set of ~ 5 undergraduate students who took the course in the previous year and who will serve as undergraduate teaching assistants for the course during a current year. Our plan is for each of these 5 students to hold a drop-in lab clinic in the Innovation Shop one day per week. In this manner, the shop would be staffed with an experienced student TA every weekday.

VI. Conclusion

We consider this to have been a highly successful, and enjoyable, experience. This pilot experience demonstrated the feasibility of incorporating a substantive hands-on component into an established, multi-disciplinary undergraduate engineering course with more than 170 students. Every lab group was able to provide a properly functioning car by the end of the final demo day. Using a set of basic but incremental asynchronous lab activities and an experiment kit distribution/supply method, we believe we have a handle on the distribution needs for future runs of this course. Moreover, we believe that this lab construct is extensible and could be successfully repeated for other courses and at other universities when the addition of hands-on and complex-system components is desired. As an example of validation of this last point, the student authors of this paper have already prepared and delivered 10 of their re-designed experiment kits to Prof. Walter Buchwald of University of Massachusetts, Boston for use in a new freshman course being offered in the new Engineering program at that University. The lab and the impacted course described here received very positive feedback from the students and have even encouraged many of them to pursue electrical project applications outside of the classroom following the end of the semester. This indicates that the lab described here not only enhances the learning of EE fundamentals but also exposes students, EE majors and otherwise, to the excitement of electrical engineering topics.

Acknowledgments

The authors appreciate and gratefully acknowledge the participation of 170+ UMass MIE students in the pilot run of this course; their feedback, collaboration, and friendship simply make all the difference. We also benefited from the expert technical advice of ECE graduate student, Izzy Masiunas, who served as graduate teaching assistant for ECE361 and Mr. Mike Jacques, a seasoned veteran of engineering projects who enjoys giving time to students. And we thank middle & high-school teachers Nick Harrison (Amherst, MA) and Tania Cezar (Framingham, MA) who, along with Mr. Jacques, developed the first prototypes of the ECE361 smart car during summer 2013. We also acknowledge several sources of funding for the research-experience-for-undergraduates that enabled time to be spent on the redesign of the experiment kits and the preparation of this manuscript. In particular, we acknowledge support by the Engineering Research Center program of the National Science Foundation under NSF Cooperative Agreement EEC-0313747; the Jerome M. Paros Fund for Measurement and Environmental Sciences Research, and the College of Engineering at the University of Massachusetts Amherst.

References

[1] "Transforming Undergraduate Education in Engineering, Phase 1: Synthesizing and Integrating Industry Perspectives", Workshop Report, American Society for Engineering Education, Arlington, VA, pp 13, May 2013.

[2] B. L. Yoder, "Two Years Later: A longitudinal look at the impact of engineering ethics education", 120th ASEE Annual Conference and Exposition report, Atlanta, Georgia, June 2013.

[3] National Research Council, "Educating the engineer of 2020, adapting engineering education to the new century", National Academy of Engineering, Washington D.C., 2005.

[4] S. D. Sheppard, K. Macatanagay, A. Colby, and W. Sullivan, "Educating engineers: designing for the Future of the Field", The Carnegie Foundation for the Advancement of Teaching, Preparation for the Professions, Josey-Bass, 2009. pp 79-81, December, 200