AC 2011-573: AUTONOMOUS VEHICLES: A HANDS-ON INTERDISCIPLINARY FRESHMAN COURSE

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Abstract

The authors have recently developed a new first-semester freshman elective, Autonomous Vehicles, as a hands-on interdisciplinary introduction to mechanical, chemical, electrical, and computer engineering, computer science, design, controls, and energy. Course goals include exposing students to many facets of engineering and computer science to aid in major choice, developing practical technical skills relevant to subsequent projects, generating enthusiasm for future studies, and developing teamwork, design, presentation, and technical writing skills. Through a series of labs including drawing and 3D printing a robot chassis, soldering a microcontroller circuit board, assembling a gear box, building sensor circuits, machining and characterizing hydrogen proton exchange membranes (PEM) fuel cells, C programming, and generating and detecting Gold codes, the students design, build, test, and optimize robots to compete in a "Capture the Flag" style game. This paper will describe the course content and summarize assessment results from the Fall 2010 pilot course.

Introduction

In Fall 2010, Harvey Mudd College began offering a new core curriculum with more electivity, including, for the first time, an elective in the fall semester of the freshman year. Most existing electives have prerequisites and are not aimed at first-semester students. As part of this curriculum revision, HMC faculty have created a variety of new courses tailored to incoming freshmen. The authors have recently completed teaching one of these courses, titled E11: Autonomous Vehicles, which offers an interdisciplinary hands-on introduction to engineering motivated by a robot design competition.

E11 has a variety of goals:

- Give students a taste of what engineers and computer scientists do to help make informed decisions about majors
- Develop design – build – test – debug skills
- Provide practical technical skills relevant to subsequent projects including
  - Machine shop
  - 3D CAD and printing
  - Soldering
  - C programming
  - Sensors and actuators
  - Analog and digital interfacing
  - Embedded control systems
- Whet students' appetite to learn more advanced topics
- Develop teamwork, presentation, and technical writing skills
- Be just plain fun!

In the context of the larger HMC curriculum, E11 also fills a number of gaps. Neither of the first two required engineering courses (E4, Introduction to Design, and E59, Introduction to Engineering Systems) involve substantial amounts of detailed design informed by technology, so most students don't get a sense of "what engineers really do" until far into their studies. Faculty have observed that sophomores struggle in the Engineering Systems course partly due to a lack of context and practical applications for the theory of systems analysis. Moreover, the required Core computer science course focuses on Python; engineering majors are presently not required to learn C programming, limiting their ability to work with embedded systems. E11 addresses these issues with a substantial hands-on team-based design problem involving C programming in an embedded context.

E11 also has a number of constraints. The course needs to be scalable to serve a large body of interested students given limited faculty teaching resources. The materials budget should not exceed $250/student. Because it is an elective with limited enrollment, students who do not take the course should not be unduly disadvantaged in subsequent courses.

A secondary objective of this effort is to give upper-division students a rich experience learning to teach. Much of the course development was performed over the Summer of 2010 by two seniors in close collaboration with the faculty. The seniors continued as members of the teaching team, each teaching a lab section, having the opportunity to present a lecture, and holding responsibility for indispensible elements of the final project. This has proven to be a powerful way to mentor young leaders and has greatly extended the impact of limited faculty time.

Related Courses

Among the many related activities, two standouts are the MIT robot design contests and the FIRST Robotics program.

Woodie Flowers at MIT established the famous 2.70 (now 2.007) Introduction to Design course in the 1960s[1]. It features remote-controlled robots and is primarily taken by third-year mechanical engineering students. In 1987, MIT established the student-run 6.270 Autonomous Robot Design contest course[2,3]. 6.270 pioneered some of the LEGO robotics that eventually entered the LEGO Mindstorms kits. Again, the class is primarily taken by sophomores, juniors, and seniors. E11 aims to be accessible to freshmen and serve as a cornerstone rather than capstone.

With Woodie Flowers's assistance, Dean Kamen founded FIRST (For Inspiration and Recognition in Science and Technology) to inspire young people to become science and technology leaders, largely through robotics competitions[4]. FIRST has activities at the high school, middle school, and elementary school levels based around large machines as well as smaller LEGO robots. E11 is based on smaller teams and emphasizes engineering science as well as the design-build-test process.

Course Organization

The E11 syllabus is shown in Table 1. E11, like most other HMC courses, is offered for 3 units of credit. Students attend two 50-minute weekly lectures in a large group and a 3-hour lab session in a group of 10. Most work takes place during the lab sessions, but students complete seven relatively short problem sets on their own time and work outside of class to optimize their robot for the final competition. First-semester freshmen receive pass/fail grading.

Table 1: E11 Syllabus

Week	Mon	Wed	Lab	Problem Set
0: 8/30		Big Picture, Energy	Shop safety briefing	
1: 9/6	Arduino Board	C Programming I	Arduino Soldering	
2: 9/13	Design Representation, Gold Codes	C Programming II	Shop tutorial 3D CAD & Printing	Welcome to Arduino
3: 9/20	Fuel Cells (L)	C Programming III	Fuel Cell Assembly	Arrrays & Feedback
4: 9/27	Energy (L)	Ohm's Law	Fuel Cell Characterization	Gold Code Generation
5: 10/4	Circuit Analysis	Capacitors & Inductors	Robot Assembly & Characterization	Gold Code Detection
6: 10/11	Diodes & Transistors	Motors	Motors & Sensors	
7: 10/18	Fall Break	Break week: no class	Break week: no lab	
8: 10/25	Feedback Control	Game Kickoff	Line-Following Robot	Energy
9: 11/1	Line Following Race	Guest Lecture: Batteries	Robot Design I	Circuit Analysis
10: 11/8	Guest Lecture: Aquatic Robots	Guest Lecture: Fuel Cell Robots	Robot Design II	Motors
11: 11/15	Scrimmage	Game Prep: no lecture	Robot Design III	
12: 11/22	Capture the Flag Game (evening event)	Thanksgiving: no class	No lab	
13: 11/29	Technical Writing	Presentation Skills	Team Writing	
14: 12/6	Robotics Show & Tell	Eng & CS Outlook	Presentations and Peer Editing	Project Report

Forty freshmen enrolled in the Fall 2010 pilot offering of the course and one dropped in the first week, leaving 39 students in the class. The class was taught by the authors: two faculty from the Engineering department and two senior Engineering majors, with guest lectures from a professor of Computer Science and several other speakers.

The major interrelated themes of the course were robotics and energy. HMC presently has a cross-campus focus on energy and sustainability and this course explored links between robots and energy, including notions of work and power; electrical, mechanical, and chemical energy; and practical issues of batteries, fuel cells, and robot performance.

Lectures

The course began with an introductory lecture giving the big picture followed by six weeks of lectures focused on practical knowledge required for the laboratories and programming. The second half of the class largely consisted of guest lectures as the students prepared for their design competition.

Labs, Problem Sets & Projects

The hands-on interdisciplinary laboratory experience formed the core of the class. The first six weeks involved tightly-defined labs in which students individually constructed a robot and fuel cell. The students then organized themselves into pairs for larger projects: a line-following race, and a game of Capture the Flag.

In the initial week, students attended an abbreviated shop safety briefing focusing on the machines they would need to use in the class. After a safety test, they received a limited qualification to use those machines under the supervision of a proctor.

In Lab 1, students received a bag of components and a blank "Mudduino" printed circuit board based on the popular Arduino platform[5]. They learned to solder, then assembled and tested their boards. Figure 1 shows the board layout and assembled Mudduino. The board contains the ATmega328 processor, a USB port for communicating with a host computer, a battery connector connected to a 5 V regulator, an H-bridge motor driver, LEDs, a buzzer, and headers and prototyping space for future expansion.

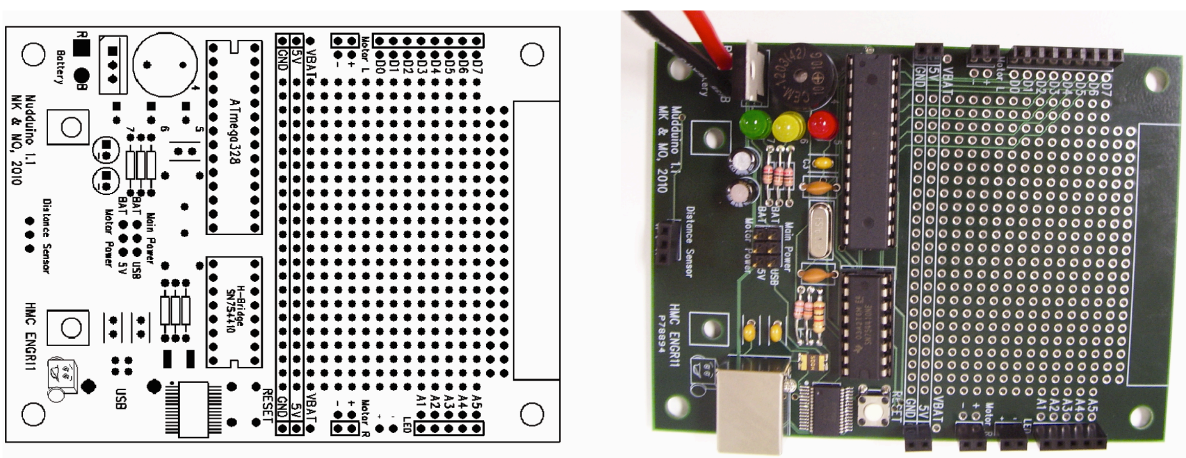

Figure 1: Mudduino Printed Circuit Board

In Lab 2, students learned to use SolidWorks to draw a chassis for their robot. They followed step-by-step instructions to learn the basic techniques, and then read the technical drawings shown in Figure 2 to complete their drawing. They then printed their chassis in ABS plastic on a Dimension SST 1200 3D printer.

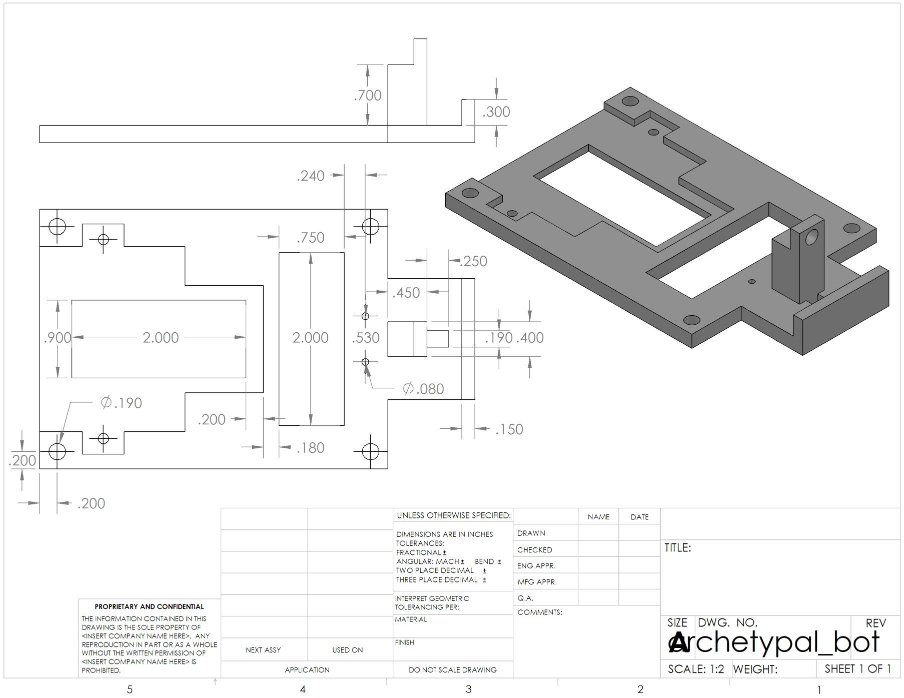

Figure 2: Chassis

In Lab 3, students went to the machine shop to manufacture components for a PEM fuel cell. They cut fiberglass endplates on a bandsaw and drilled holes on a drill press for the bolts and gas connectors. They machined a pattern of holes in a graphite flow plate using a mill with a coordinate measurement device. They also painted platinum catalyst ink on Teflon-treated carbon paper to construct gas diffusion layers, and cut gaskets from silicone rubber. In Lab 4, the students then assembled the fuel cell by sandwiching a Nafion proton exchange membrane between the various layers and bolting the stack together, as shown in Figure 3. They used a benchtop electrolysis machine to produce hydrogen, and then connected their fuel cell to convert hydrogen and oxygen into water and electricity. They characterized the current and voltage of the fuel cell across varying loads to produce a power curve and determine the maximum power capability. This fuel cell design has an unacceptable weight-to-power ratio for use on mobile robots, so it was intended to power stationary beacons on the Capture-the-Flag field instead.

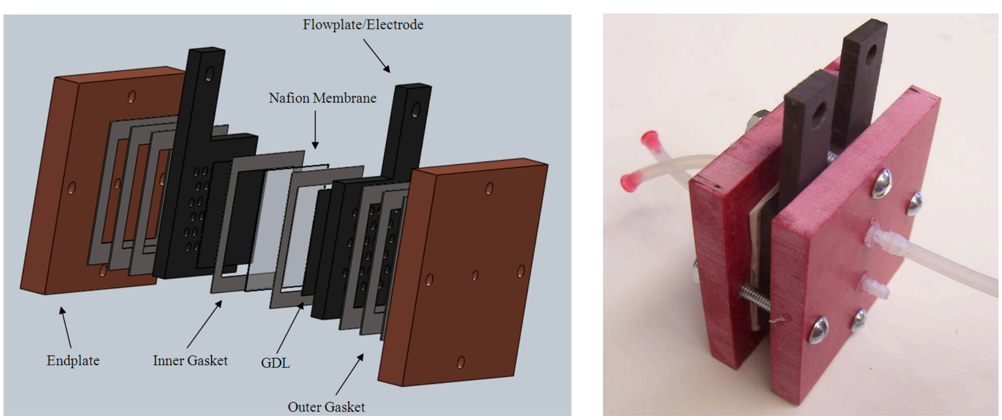

Figure 3: Fuel Cell

Meanwhile, students completed a set of four problem sets to learn to program the Arduino in C. The problem sets involved

- performing calculations and printing to a terminal on a host laptop
- controlling the LEDs and buzzer (including delays and randomness)
- building a reaction timer game
- building a "Simon says" memory game
- generating Gold codes
- detecting Gold codes

In Lab 5, students assembled a gearbox kit and mounted motors and gears on their chassis. They soldered resistors on their Mudduino board to interface with an IR reflectance sensor and a phototransistor. They attached a connector to their battery pack, stacked the battery and board on the chassis, and bolted the whole robot together, as shown in Figure 4. In Lab 6, students learned to control the robot in C. They developed their own library of motor control functions. They learned to read the sensors, and programmed the robot to drive toward a light, stopping if it were about to dive off the lab bench. They attempted to drive in a square and learned about the limitations of open-loop control.

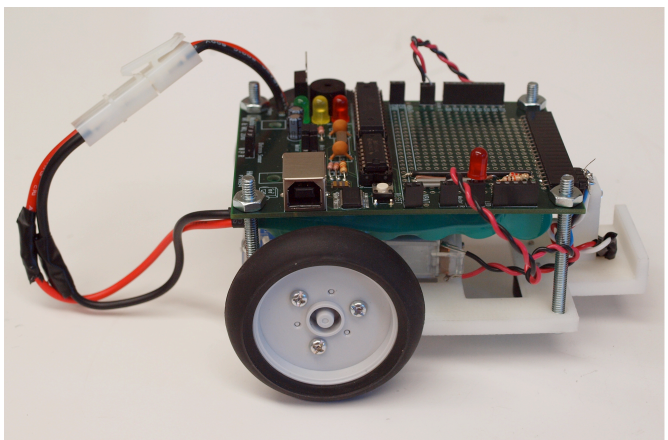

Figure 4: Assembled robot

In the second half of the semester, students paired up into teams. They first programmed their robot to follow a line, performing closed-loop control based on a reflectance sensor. They optimized their line-following algorithms and held a race in which robots chased each other around large square patterns on the floor of the building.

For the final design contest, the teams developed robots to play a game of Capture the Flag on a 4' x 8' playing field, shown in Figure 5. Eight beacons are located around the border of the field; initially four are blue and four are yellow. Bump sensors on the beacons flip the color of the beacon when depressed. Each robot is arbitrarily assigned to play blue or yellow, seeking to convert all of the beacons to its own color. Each beacon broadcasts a unique Gold code by flashing an LED on and off at 4 KHz. The Gold code inverts based on the color of the beacon, allowing a robot to identify both the beacon number and its color. A black line leads from the starting position to one of the beacons, allowing a robot to capture at least one beacon by simply using its line following algorithm. To find other beacons, the robot must lock onto their Gold codes.

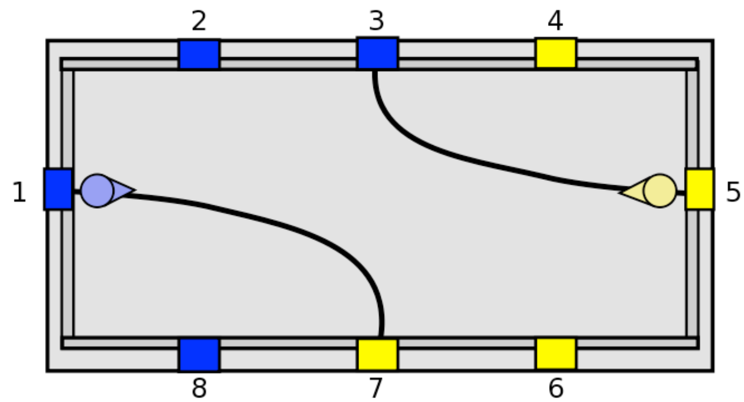

Figure 5: Playing field

Each game lasts two minutes. At the end of the game, the robot with the largest number of beacons wins. If the score is tied at the end of the game, it is decided by sudden death in overtime. If both robots are incapacitated (e.g. flipped over) at the start of overtime, their designers may return them to the starting zone.

Each team is required to modify their hardware in at least one useful way in addition to developing their software. The hardware modifications this fall included adding a distance sensor or extra side-mounted phototransistor, stacking two Mudduino boards for dual-processing (one controlling movement and the other continuously seeking Gold codes), redesigning the chassis to reposition sensors, and mounting an Airsoft pellet gun to shoot beacons from a distance.

Problem Sets

In addition to the labs and programming problem sets, the students completed three short problem sets covering energy, analysis of circuits with resistors, 1st order circuits, a speaker driven by a transistor, and the transient and steady-state behavior of a motor.

Assessment

We assessed how the course met learning objectives through a combination of rubrics evaluating student work and surveys examining student attitudes. Because this course was first offered in Fall 2010, no longer-term assessment is currently available, but plans for the future include major declarations for former students and performance in computer science, introductory engineering design (if applicable – only engineering majors are required to take this course), and required physics courses. In all cases, results of these metrics will be compared with students who requested this course as an elective but did not get in due to the class size limitations.

Overall, the pilot offering of Autonomous Vehicles was highly successful and met all of our goals. Most of the freshmen entered with little experience in engineering or programming and wrestled with following step-by-step directions in the labs and with writing simple programs. The students matured tremendously over the semester and developed impressive capabilities. With little direction from the instructors, every team was able to field a functional robot addressing a complex challenge. The students also enjoyed the class and rated it highly in the teaching evaluations. For example, the average score for "I learned a great deal in this course." was 6.74/7 where 7 is "strongly agree"; "The course stimulated my interest in the subject manner" received a 6.50/7. Evidence of success related to specific course goals is detailed below.

- **Give students a taste of what engineers and computer scientists do to help make informed decisions about majors**
  On a five-point Likert scale where 5 corresponds to "strongly agree", students rated the statement "I feel better informed about what engineering and computer scientists do" a 4.6/5 and "E11 affected my choice of what to study at HMC" a 3.8/5.

- **Develop design – build – test – debug skills**
  In addition to instructor observations of improvements in students' skills in these areas, students rated "E11 improved my skills in" design a 4.3/5, building hardware a 4.5/5, and troubleshooting a 4.6/5 on the 5-point Likert scale.

- **Provide practical technical skills relevant to subsequent projects**
  While the ability to transfer skills to subsequent projects cannot be measured for several semesters yet, the course was designed to provide at least an introduction to all of the skills in the list. All of the students succeeded in building operational robotics using each of the skills on the list. Additionally, indirect evidence from student surveys indicates that students believe that E11 improved their skills in design, building hardware, programming, and troubleshooting.

- **Whet students' appetite to learn more advanced topics**
  Student evaluations of teaching rated "The course stimulated my interest in the subject manner" 6.5/7. In the end-of-course survey, students showed the most interest in learning more about programming (4.6/5), mechanics (4.4/5), and electronics (4.3/5), but were less enthusiastic about further studies in chemical engineering (3.0/5, or neutral).

- **Develop teamwork, presentation, and technical writing skills**
  Rubric scores from student presentations showed solid performances on presentations (students averaged, 3.6/5 on where 5 is "Exemplary", and 1 is "Poor") and reports (average of 3.1/5 on the same scale). Based the 5-point Likert-scale survey, students felt that the course did help improve their skills in teamwork (4.1/5), presentations (3.5/5), and technical writing (3.7/5).

- **Just plain fun!**
  "I enjoyed the class" received an average score of 4.7/5 on the student survey and 9/37 survey respondents called the course "fun" without any prompting in response to the open-answer questions "Did this course meet your goals and expectations? Why or why not?" and "What went well for your learning in the course?"

The full set of responses is to the end-of-semester survey is shown in Table 2 below.

Table 2: Results of End-of-Semester Student Survey on Topics and Interests

Topic	1 strongly disagree	2 disagree	3 neutral	4 agree	5 strongly agree	Average
I feel better informed about what engineers and computer scientists do.			2	10	23	**4.6**
E11 affected my choices of what to study at HMC	2	2	6	19	8	**3.8**
E11 improved my skills in:						
design			4	17	15	**4.3**
building hardware			1	15	20	**4.5**
programming		1	1	14	18	**4.4**
trouble shooting			1	11	24	**4.6**
teamwork			7	17	12	**4.1**
presentations		3	15	14	4	**3.5**
technical writing		1	13	18	4	**3.7**
In the future, I would like to learn more about:						
electronics			5	14	17	**4.3**
mechanics			7	10	20	**4.4**
chemical engineering	3	10	11	9	3	**3.0**
control systems	1	1	10	12	12	**3.9**
programming			3	9	24	**4.6**
differential equations	1		12	14	9	**3.8**
CAD/machine shop		2	8	10	16	**4.1**
I enjoyed the class			2	7	27	**4.7**
I would recommend the class to freshmen next year			2	7	27	**4.7**

The final design competition proved to be at the right level of difficulty: accessible but challenging, with a mix of skill and luck required. All teams were able to meet the basic elements of having a robot move and detect beacons. A couple of the weakest teams were unable to combine these two elements and make their robot consistently press a beacon that they had found. The more successful teams mostly built robots with side-mounted distance sensors and phototransistors. They orbited the board using the distance sensor to maintain a desired distance from the wall. When they detected a beacon, they turned to ram it, and then continued their orbit. The best robots were distinguished by their speed, their ability to rapidly and consistently detect beacons, and their ability to avoid the other robot rather than become tangled in a collision. Detecting beacons is a processing-intensive task and skillful programming or dual processing makes the difference between robots that can drive smoothly and robots that move jerkily or miss beacons due to processing time. Contests were exciting and suspenseful to watch.

The final competition drew an audience of about 150 students, faculty, and staff, filling a large lecture hall with a cheering crowd.

We also found a good balance of individual learning and teamwork. By completing the labs on their own, students all mastered the fundamental skills. By entering the final competition in pairs, students learned to work together and partition tasks. As compared to upper-class students with more teamwork experience, the freshmen were initially immature. Several teams were initially dysfunctional, with the students growling at each other or ceasing to communicate. But by the end of the project, each team had developed into a cohesive unit that could effectively divide the labor and accomplish more than either individual. Many teams divided labor between the hardware and software aspects of the project, coming together for debug and integration. As each team had two robots, the teams could usually work around hardware failures rather than requiring assistance from the instructors.

The labs uniformly consumed the full three-hour block, with a few students staying up to half an hour late each week. The fuel cell labs were the most difficult. The materials were difficult to machine (particularly the brittle graphite) and the fuel cells tended to leak through the gas port connections or between layers if not tightened enough or to crack if overtightened, so only a handful students obtained the expected power of ~ 100 mW. Next time, we plan to switch to acrylic end plates and aluminum flow plates, tap the acrylic so that gas ports can be screwed in, and use a more robust gasket and conduct more testing by inexperienced students. The Mudduino board and sensor mounting had a number of minor inconveniences, so we plan to redesign it for improved ease of use.

Survey results for lab outcomes are shown in Table 3, and confirm the success of most labs, with the biggest changes needed for the Fuel Cell lab.

Table 3: Results of End-of-Semester Student Survey on Lab Outcomes

E11 Autonomous Vehicles Survey: Lab Outcomes	Number of Responses
1) Expected Major:	
Engineering	17
CS	12
Other	4
Undecided	4
2) My printed circuit board in Lab 1 worked:	
a) on the first try	22
b) with minor repairs in the lab session	12
c) only after help outside lab from the teaching staff	3
3) My robot chassis in Lab 2 printed correctly:	
a) using the file I first submitted to Willie Drake	32
b) after sending a corrected file but with only one printing	3
c) on the second or later printing	0
d) never	1
4) My fuel cell:	

a) broke before it could be tested	1
b) sat like an inert lump of coal and produced no measurable power	6
c) produced less than 20 mW of power	25
d) produced more than 20 mW of power (unusual this year)	6
5) My sensors worked:	
a) on the first try	21
b) with minor repairs in the lab session	13
c) only after help outside lab from the teaching staff	2
6) My team's robot in the line following race	
a) couldn't consistently follow a line	0
b) consistently followed a line but significantly malfunctioned during the race	9
c) consistently followed a line and performed as intended during the race	12
d) part C and won at least one race	15
7) My team's final robot: (check all that apply)	
a) could consistently detect beacons with the phototransistor	28
b) could consistently claim at least one beacon during testing	33
c) had erratic behavior that my team could never debug	6

The most difficult lecture topic areas for the students were C programming and differential equations (DEs). The lectures on C assumed that students were already comfortable with general notions of programming and taught the language by example. Many students lacked adequate background to absorb the language in this fashion; next time, we will need to devote more attention and start with the foundations. The problem sets also need to explicitly test beacon-detection code on real beacons. Most students had not studied DEs before and the 5-minute introduction to guess-and-check solution of first-order equations proved insufficient. Further lecture time should be devoted to this in the future (although the students agreed with the statement "In the future, I would like to learn more about differential equations" in the survey).

Conclusions

Overall, Autonomous Vehicles was a highly successful hands-on interdisciplinary course that achieved many goals, especially those of giving students a preview of what engineers and computer scientists do and building enthusiasm for future learning in these fields. The course will be taught again in Fall 2011 to 50 students, and many of the freshmen from the first year will serve as laboratory assistants. We look forward to seeing the longer-term effects of the course on student performance in subsequent classes whose material may have been motivated in this course and their persistence as engineering and CS majors.

Acknowledgments

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