Control Education via Autonomous Robotics

Linda G. Bushnell and Andy P. Crick
Department of Electrical Engineering
University of Washington, Seattle, WA 98195-2500, USA
bushnell@ee.washington.edu; andyc@ee.washington.edu

***Abstract*—This paper details the development and implementation of three courses on autonomous robotics that are offered at the University of Washington. The three-course sequence is now in its fourth year. The structure of each course will be discussed along with wisdom on what worked and what did not work. It is hoped that this paper will be of use to others developing hands-on, creative courses in control systems and robotics.**

I. Introduction

There is much recent discussion in the controls community on how to better teach control systems concepts to engineering students. Many students take control theory courses, but few retain the details of the skills learned. The quest for a new way of teaching control theory concepts, or other concepts such as artificial intelligence, has lead educators to explore methods involving hands-on and creative design work involving robotics [15], [13], [8]. For example, the RoboCup [21], [22], [23], [9] international robot soccer tournaments have become a huge success in teaching artificial intelligence, computer vision and control systems concepts, in addition to team-building. The RoboCup teams are typically large (30-40 members), sponsored and work for twelve months preparing their team of robots, while building on prior years' knowledge. In contrast, MIT's 6.270 Autonomous Robot Design Competition [19] is a smaller-scaled version of the RoboCup "small-size" league. It involves mobile, autonomous robots (based on LEGO pieces [16]) offered during the month of January to undergraduate students at MIT. The 6.270 robot competitions vary each year, from egg gathering to sorting to ping-pong. The duration of this type of course precludes extensive exploration of advanced control systems concepts.

Between these two extremes lies a middle-ground structure that has been used as a regular, budget-limited semester or quarter university-based course for engineering students. Some examples are as follows. Halmsted University offers a robot design competition that is part of a one-semester course on mechatronic systems [11]. Previous competitions involved autonomous LEGO mobile robots in games of golf, soccer, environmental clean-up and navigation. Case Western Reserve University offers a semester-based course on autonomous mobile robotics [3], [6], offered twice a year, which has a popular egg-hunt competition. Carnegie Mellon University offers a semester-based course [7] in autonomous multi-robot systems. This is a hands-on class focused on artificial intelligence in which students develop and evaluate a multi-robot system via simulation or in hardware. Brigham Young University offers a semester-based senior design project [4], [2], [1] in robot soccer as a capstone design experience. The University of California at Davis offers a 5-credit course spread over three quarters involving the popular Micro-Mouse competition [10].

In the Autumn quarter of 2000, the first author was challenged with taking over and updating a senior-level capstone design course titled "Principles of Mobile Robotics" at the University of Washington (UW). Using the wealth of resources available for this type of course, everything went smoothly and with great success. However, in searching for a way to bring research-level control systems concepts to undergraduate students, it was found that one quarter-long course did not provide enough time for exploration. This motivation led to the design and development of two more quarter-based courses on autonomous robotics, emphasizing the combination of control, communication and computation. As a set, all three courses promote creative, hands-on control systems and robotics design.

The purpose of this paper is to describe the design, development and subsequent modifications to the three-course sequence on autonomous mobile robotics so that readers may be able to start similar courses. The courses are continually being updated even to this day. This paper will discuss what worked and did not work and will include assessment comments from the students. This paper is organized as follows. In Section II, commonalities between all three courses are discussed. The following three sections describe each course in detail. In Section VI, various issues involved with the courses will be discussed. In the last section, conclusions are given.

II. Common Features

All three courses are 4-credit, quarter-based courses that have three hours of lecture per week. The laboratory is open at all hours, but has scheduled 3-hour blocks per student team per week where the Teaching Assistant (TA) is available to answer questions. The average time spent in the lab per week is 15 hours. The competitions are held in lieu of the final exam during the eleventh week (finals week) of classes. The first course is a pre-requisite for the second course, while the third course is offered as a graduate-level course.

During the first six to seven weeks of each course, the hands-on laboratories consist of assignments to build up the skills of the robots (and students). Each laboratory assignment requires a laboratory report grade and a laboratory work grade. A formal technical report is written by each team for each laboratory assignment. For the laboratory work grade, the students must demonstrate various parts of the laboratory skills to the TA. The remaining weeks of the quarter are spent on project design for the robot competition.

Each student team is given a kit for the laboratory consisting of LEGO [16] parts, motors, sensors and a Handy Board [12] microcontroller board (bought on recommendation from other existing courses). Course-specific parts, such as receivers and transmitters, are added to the basic kit as needed. The lab kit is not available commercially, but a parts list is available through the authors. The total cost for one kit is approximately $900. The Handy Board is based on the Motorola 6811 microprocessor with 32K of static RAM. The students use Interactive C [14], the programming environment created for the MIT LEGO Robot Design project, to write programs that are then downloaded to the Handy Board, which is situated on the robot. Interactive C is a multi-tasking, C language based compiler that includes a user command line for dynamic expression compilation and evaluation. The focus on C programming does not limit the achievements or performance of non-EE/CSE students.

In addition to the lectures and laboratory, the students write a design proposal, discuss their design in front of the TA, lab mentor (a volunteer from the digital electronics industry) and professor, write a final technical report, and have a formal technical presentation in front of the TA, lab mentor and professor after the competition. The proposal, final report and presentation cover similar topics for all three classes. For example, the first course's final report guidelines require the following content.

- Introduction: Summarize you robot's strategy and design, your team's strategy, and briefly describe you robot's performance. Describe the general scope of the project that you completed.
- Mechanical design: Include detailed sketches of the mechanical design and a digital photo of your final robot. Explain in detail how things work. Explain why you build the robot the way you did. If there was some key feature that came out of a preliminary design, or as a reaction to the failure of a preliminary design, please describe it.
- Software design: Include flow charts for the overall control software and all behaviors. Explain in detail how the software works. Explain why you designed it this way and not some other way. Include (as an Appendix) a complete commented listing of the final code.
- Performance evaluation: Discuss in detail how your robot performed during the skills tests and competition. Describe what worked and what didn't work. Evaluate the robustness of your hardware and software. Make a list of any perceived shortcomings and describe what you would do to improve them.
- Conclusion: Summarize the whole project.

Instead of performance evaluation and conclusions, the project proposals include sections on preliminary results, budget, time table and schedule.

All courses have extensive web sites that list the syllabus, lectures, homework, laboratory assignments, competition information, report guidelines, documentation and relevant links. The format given in [20] was used to design the web sites.

III. First Course: Basic Principles

The first course of the sequence, EE462, is titled "Principles of Mobile Robotics." The majority of the students taking the course are seniors in Electrical Engineering. Some juniors and first-year graduate students (in EE, ME and Aero/Astro Eng.) also take the course. The focus of the first course in the sequence is on learning the basic principles of sensors, actuators and PID control.

Initially, the course was designed using the textbook by Fred Martin [18]. The first author created PowerPoint slides, with permission of the publisher, for use in lectures [5]. The course is designed to have two parts. The first part is the three hours per week of lectures. These lectures mainly focus on the textbook, containing information on all hardware and software used in the laboratory, reactive control schemes, algorithmic control schemes and general principles of autonomous robot design. Guest lecturers include industry engineers, the (local) Seattle Robotics Society and students participating in independent study projects with the authors. Videos from the MIT course and other similar robotics courses are shown.

The second part of the course is the hands-on laboratory. The first six weeks of the laboratory are spent on one-week team assignments as follows. The students are given the basic UW lab kit, containing LEGO parts, motors, sensors and a Handy Board microcontroller.

- Laboratory 1, A Basic Robot - building the UW version of the HandyBug [18] robot.
- Laboratory 2, A Forest Wanderer - programming in Interactive C (IC) to make the robot move.
- Laboratory 3, Motors - exploring various motors in the kits.

- Laboratory 4, Telemetry and Shaft Encoding - learning dead-reckoning via shaft encoding and learning how to store and dump data for analysis.
- Laboratory 5, Sensors - exploring various sensors in the kits.
- Laboratory 6, PID Control - controlling the robot in a circle and in a spiral.

After finishing these laboratories, the students have a good idea about PID control and how to make their robot perform various tasks. During the sixth week, the student teams prepare a proposal on their competition robot. Once approved, the students start building their final robot that will compete in a game of one-on-one robot golf.

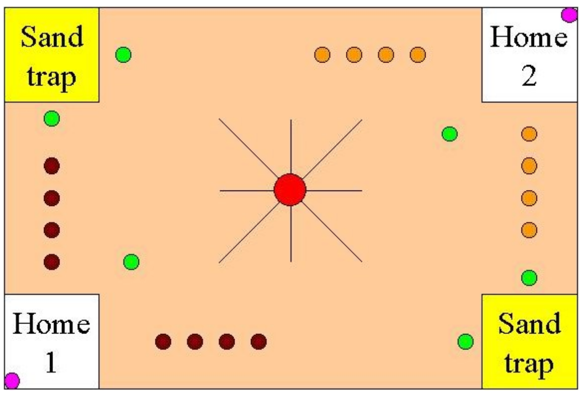

Fig. 1. The EE462 golf competition table. There are two home bases, two sand pits, one golf hole and locations for 16 golf balls.

To better prepare for the competition, skills tests are required for all teams in weeks seven, eight and nine. The skills tests are performed on the competition table – a golf table, 4-foot by 6-foot with a 3-inch hole in the middle. Figure 1 shows the competition robot golf table, with two home bases, two sand pits, four trees, two polarized lights at the home bases, and sixteen locations for the initial golf ball locations (eight for each robot; two different colors). For EE462, the skills tests are as follows.

- Skills Test 1: With your robot starting in one of the home bases on the robot golf table, demonstrate that it can find the golf hole, then return back to its home base.
- Skills Test II: With your robot starting in one of the home bases, demonstrate that it can get one of the golf balls into the golf hole.
- Skills Test III: With your robot starting in one of the home bases, demonstrate that it can get two golf balls in the golf hole. One ball will be placed on each side of the home base.

The competitions are held during the final exam slot. The competition for this class is a one-on-one golf tournament, in a double-elimination playoff format, using the table as shown in Figure 1. The two robots (restricted to 9-inch cube) start in the opposite home bases and have eight colored balls to get in the hole. Robots are ranked on the number of their balls that are put in the golf hole. Figure 2 shows two robots in the Autumn 2002 golf competition.

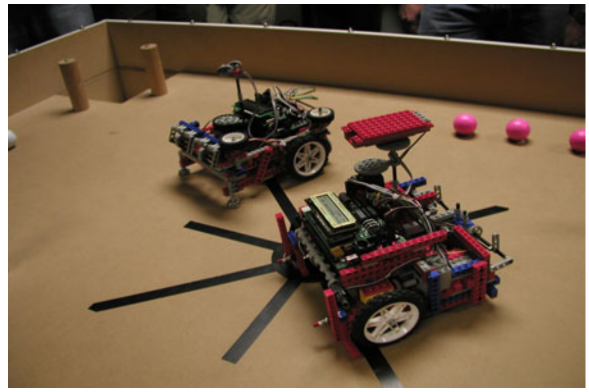

Fig. 2. Two robots competing in the EE462 golf game in December 2002.

Available assessment material included end of quarter course evaluations and an informal questionnaire given in the fourth week of the class. Course evaluations at the end of the course indicated that students wanted more class discussion and videos about other robot designs. Having PowerPoint slides for most of the lectures gave a mixed reaction from the students. Some wanted more interactive classes. All of the students liked having a lab mentor in the laboratory. The students are happy with the laboratory structure. Suggestions for improving the course lectures and overall structure are as follows.

- Overall Course Structure: The learning in the class is happening in the laboratory as well as in the lecture hall. The current structure of three hours of lecture plus three hours of lab per week is not efficient. The students are spending an average of 15 hours per week in the laboratory. It is recommended to modify the class schedule to have two hours of lecture per week and six hours of laboratory per week. Alternatively, the credits for the course could be increased to 5.
- Lectures: The lectures could be improved by containing more material on control theory and how it is used in robotics. The eight PowerPoint lectures from Fred Martin's book should be posted as background reading material for the students.

IV. Second Course: Wireless Communication

In the second course, EE463, "Autonomous Robotics," emphasis is placed on integrating feedback control and wireless communication by using similar robot platforms as in the first course.

The lectures focus on digital control systems, precise positioning, wireless networks basics, RF basics, diagnostics, calibration, flowcharts, data flow diagrams, multi-tasking, debugging, completeness and quality. The term “precise positioning” is used not to mean “precision positioning,” but rather to mean using a digital control system to determine the “right place” for the robot, and to cause an electro-mechanical positioning system to end up in the right spot. It is typically iterative: “where should I go? where am I? and what should I do to get there?”

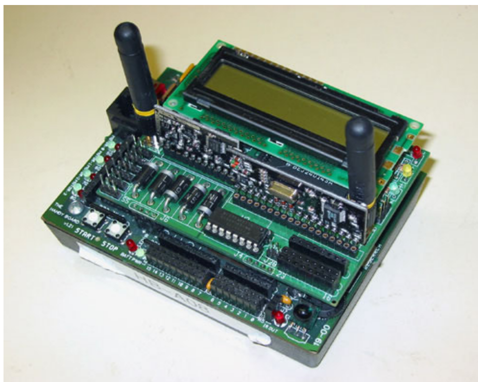

Fig. 3. The UW’s RF expansion board, with two antennas, on top of a Handy Board. An LCD screen is mounted on the top

The communications protocol used in the class is a simple, half-duplex, polled, master/slave protocol, which operates at 900MHz. It is intended to provide a programatically straightforward scheme in which a slave can submit a request and receive a reply; and in which a master can send unsolicited messages to a slave. This protocol traces its lineage back to a polled asynchronous protocol called TINET that was developed by Texas Instruments for use in non-secure banking applications, such as credit card verification systems. It requires a layered protocol where the packets are encrypted and transparent and the scheme is non-interrupting and unbuffered. Understanding un-buffered wireless communication is the most challenging part of the course. The wireless network consists of two nodes, one of which is the robot and one of which is the “master” computer. Both the master computer and the robot have a receiver and/or a transmitter. In order to implement wireless networking on the mobile robot platform for this course, the lab mentor designed a new expansion board for the Handy Board microcontroller board. This “UW RF expansion board” contains one receiver chip and one transmitter chip, both from LINX Technologies, Inc. [17]. Figure 3 shows the UW expansion board (along with the Handy Board and LCD screen).

Under the quest to continually improve the courses, new lecture ideas were brought to the course. To encourage the students to attend all of the lectures, simple homework is given for each lecture. This involves searching on the Internet for a specification on a part used in the course. For example, sample questions include “For the part QRD1114, what distance between the sensor face and the reflective surface is the device specified?” and “For Texas Instruments SN754410, what is the purpose of the diodes in Figure X?” In addition, simple pop quizzes are given at the beginning of most lectures, which ask the students to recall important concepts from previous lectures, for example. The midterm format, which was used in the first year of the course and dropped in the second year, came back in year three as a report on a control system design failure that “killed at least one human being and/or did at least $1m of damage.”

Fig. 4. The EE463 maze table used in lab assignments.

The structure of the laboratories is similar to the first course, but is more focused on in-depth, hands-on work in wireless communication. The students spent many hours learning unbuffered wireless communication protocols. The second through fifth labs use a maze table, as shown in Figure 4, to learn new skills. There are six weeks of lab assignments as follows. The students are given the basic UW lab kit with the modified expansion board.

- Laboratory 1 (1 week): Bump & Grind - constructing a simple robot and programming in IC a basic collision avoidance and reliability task.
- Laboratory 2 (1 week): Maze: end to end - designing for a basic autonomous maze exploring task.
- Laboratory 3 (1 week): Maze: stop and go - the robot must move to specific maze locations (denoted by letters in Figure 4) that are specified in a manually entered list.
- Laboratory 4 (2 weeks): Basic wireless commands - the robot must interact by RF wireless with a master computer that will command it to “stop,” “go,” “turn around,” etc.
- Laboratory 5 (1 week): Maze: wireless target des-

ignation - a version of Lab 3 in which the list of locations is replaced with "go to location X" commands from a master computer via a wireless link.

The key concept learned in the laboratories is unbuffered wireless communication. For example, in Lab 4, where the basic wireless ideas are introduced, the students are given a sample networking software program to navigate the maze table and are asked to modify it to perform the following steps:

1. Initially wait until the start or stop button on the Handy Board is pressed and then use the one that was pressed as an indicator of the starting location.
2. Initialize the wireless link and respond to polls.
3. Build an appropriate maze location request packet.
4. Wait for a poll from the master computer.
5. Transmit the request to the master.
6. Wait for, and then acquire, the reply from the master.
7. Integrity check the reply.
8. Extract the next maze rectangle address from the reply.
9. Move forward or backward as appropriate.
10. Wait five seconds.
11. Repeat steps 3 through 10 for a total of 15 iterations (for reliability).

Additionally, the code provides sufficient error recovery capability such that the wireless link operates reliably in spite of the random electronic noise in the lab.

The control theory concepts from the first course, EE462, such as PID control with the shaft encoder sensors, are also emphasized in this course. In addition, the students learn how to combine the control feedback code with the wireless networking code in order to make their robot do what they want it to do. On top of that, the students are limited in computation by the Handy Board computer, not only in memory size, but also in speed of computation.

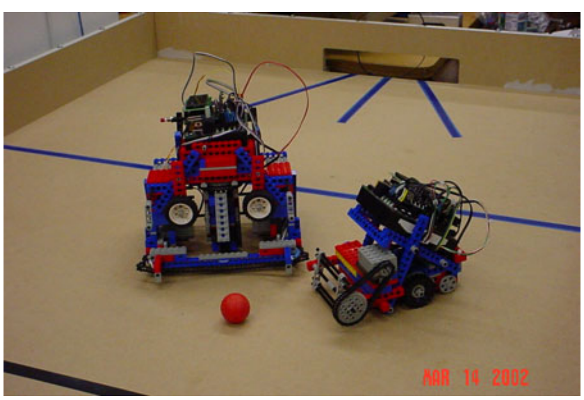

Fig. 5. The EE463 foosball competition in March 2002.

After the above laboratory assignments are completed, the students are required to do three skills tests to prepare for a robot foosball game. The skills tests are performed on the robot foosball table, partly shown in Figure 5. This competition table is 4 feet by 6 feet with polarized light at each goal, two different colored off-sides lines (black and blue), a 12 inch by 3 inch goal opening on each end, four "throw-in" locations and two ball-entry cups. The robots are a bit smaller than the ones used in the EE462 class - they must fit in an 8-inch cube.

- Skills Test 1: Demonstrate the ability to reliably obey the referee - the robot must demonstrate its ability to obey a set of commands (such as "game start," "half time," "game end," etc) sent from a master computer via a wireless link.
- Skills Test 2: Demonstrate the ability to find and capture a loose foosball - the robot must demonstrate the ability to reliably find and capture a loose foosball upon command by a master computer via a wireless link.
- Skills Test 3: Demonstrate the ability to score a goal - the robot must demonstrate the ability to reliably find and capture a loose foosball upon command by a master computer via a wireless link and then deliver the foosball to a designated goal.

Skills Test 2 requires vision data. To accomplish this, a camera (web cam) is mounted above the foosball table and wired to the master computer. The robots then are able to request x-y position data for the foosball, their opponent and themselves from the master computer.

Robot foosball is similar to robot soccer, but a real foosball is used and the ball enters the start of the game rolling. Seeding games, run the weekend before the competition, are formally refereed games in which robots compete to obtain an advantageous starting position (in the double-elimination schedule) for the final competition. These seeding games also provide an opportunity for testing against a real opponent. In the robot foosball game, robots compete two at a time to find and capture a loose foosball and deliver it into the robot's assigned goal. Figure 5 shows a photo from the EE463 foosball competition from Winter 2002 quarter.

Available assessment material included input from the students during week four. The students were asked the following questions:

LECTURES

1. Are you able to follow the lecture? What part of the lecture material are you not clear about? What would make this material clearer for you?
2. How well is the professor keeping you motivated to learn?
3. What are the most important points covered in lecture so far?
4. What additional topics would you like to cover in the lectures?

LABORATORY

1. Do you have any suggestions on how to make the laboratory better?
2. Do you like having a laboratory mentor in addition to a TA?
3. Is your team working well? Do you have any conflicts with your teammates?

Review of these materials indicated that the students wanted more board writing, more interaction, more elaborate instructions with sample code, videos of robot competitions, case studies, more showing of props in class, more discussion, more lab demos, more game-playing strategies, discussion on artificial intelligence, fuzzy logic and neural networks, overview paragraph in the lab assignments, and research opportunities. From this questionnaire, the class was re-directed mid-course to include more guest lecturers, lab demos, overviews in lab assignments, sample code, more videos, lectures on neural networks and fuzzy logic, more case studies and videos of other relevant robots.

Course evaluations at the end of the course indicated that students liked the laboratory part of the class. They did not like the Cognachrome Vision System, which was used in the first year offering. The students were very pleased with having a lab mentor in the laboratory.

V. Third Course: Multi-Robot Systems

The third course, EE545, "Autonomous Multi-Robot Systems," has a similar structure as the above two courses, but the students must design and build a team of three autonomous mobile robots that will achieve coordinated control via peer RF communication in a game of air hockey. This course is offered as a graduate-level course open to undergraduates.

The lectures have had different structure, depending on which author is teaching the course. In one case, the main part of the lecture time is taken by student presentations on papers from the literature. In the other case, the lectures focus on technical design detail for multi-robot systems.

The students are given the same lab kit as in EE463 for each robot. The labs start off with two-person teams that build one offense/defense hockey robot. Three of these teams are then combined to create a team tasked with putting together a three-robot team, where one of the three robots is redesigned to be a goalie. Each robot (restricted to 8-inch cube) is built to have two-way wireless communication capability. Two robots "talk" to each other via the master computer via the RF link. Buffered protocols are used in this course, vs. the unbuffered in EE463, to make the design easier. Requests to the master computer are on one channel, e.g., Channel A, and received signals are on another channel, e.g., Channel B. A web cam camera mounted on the ceiling above the competition table is wired to the master computer. Thus, the robots can request camera data, consisting of robot and hockey puck x-y locations, from the master computer.

Three laboratory assignments, covering seven weeks, are given as follows.

- Laboratory 1 (3 weeks), Build Air Hockey Bots: build robots for the air hockey game; write diagnostic code (groups of two).
- Laboratory 2 (2 weeks), Claim a Puck: focus on robot peer communication. Three robots plus one puck will be on the table. One of the robots needs to "claim" the puck and communicate this to the others.
- Laboratory 3 (2 weeks), Push a Puck: each robot turns to face another robot and shoots the puck at it. Focus on getting wireless peer communication and camera system working.

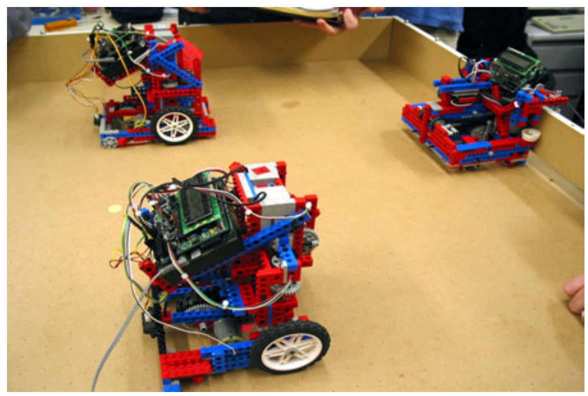

Fig. 6. The EE545 air hockey competition in June 2002.

A 4-foot by 7-foot air hockey table was constructed for the laboratories and competition. Two air hockey pucks were glued together to create a puck that could be manipulated by the wheeled robots. Figure 6 shows a set of three robots that were used in the robot air hockey competition in Spring 2002. There are two offense/defense robots and one goalie. The offense/defense robots in this photo had the mechanical advantage of a unique 3-state transmission system (forward/reverse, spin, and neutral). The goalie was uni-directional. All three robots used quadrature shaft encoding.

The skills test, which are run the few weeks before the competition are as follows. Different skills are required for the offense and defense modes.

- Skills Test 1: Offense mode: static shoot and score on an open goal from 5 well-defined locations. Defense mode: block 3 out of 6 shots directly shot at it, plus any 3 out of 12 of non-direct shots.
- Skills Test 2: Offense mode: locate a stationary puck, move to it, turn and shoot on an open goal.

Defense mode: same as Skills Test 1 but must stop all pucks directly shot at it plus any 6 of the 12 other non-direct shots.

Course evaluations at the end of the course indicated that students liked the laboratory part of the class. The students were divided on having the student paper presentations. Suggestions for improvement include: give a more formal "objectives" statement to the laboratory assignments and have more lectures on multi-robot systems. Exit interviews showed that most students liked the format of the class and enjoyed having a lab mentor in the laboratory.

VI. Discussion

There are many things that worked and did not work for the three courses. Course-specific improvements are stated above. In general, there are a few items for overall course structure that should be mentioned.

What worked?
There are many things that worked well for these three courses. The students knowledge was broadened by inviting guest speakers from industry and the Seattle Robotics Society to the lectures. The students were not restricted to certain hours in the lab due to the open laboratory structure. The laboratory mentor not only build our three competition tables, but spent endless hours in the laboratory, one-on-one with the students. Having someone with digital electronics expertise was a big plus to all three courses. Having the robot competition tables available for robot design and testing during the middle of the courses worked out best. Including videos in the lectures, discussing neatness and design quality and "what to put on your resume from this course" all helped to improve the courses. Having one-week laboratory assignments (for the first two courses) helped keep the students focused to the project at hand. Giving questionnaires during the fourth week of the course helped in redirecting the course. The instructor did not have to wait for the end-of-course evaluations to start improving the course.

What did not work?
There are many ways to improve this sequence of autonomous robotics courses for engineering students. Things that did not work well in the courses included having three students in one team (for the first two courses). It was much better to have two-person teams. Also, using a textbook in EE462 worked out well at first, but became dull for the students. We recommend that it only be used for background reading. The authors also encourage readers to search the current microcontroller market for low-cost alternatives to the MIT Handy Board. In addition, instructors may benefit from an outcome-based assessment for such courses.

VII. Conclusion

A creative, hands-on, three-course sequence on autonomous mobile robotics for engineering students is presented in this paper. The popular LEGO-based autonomous mobile robotics course serves as the first part. This is expanded on to include concepts of RF wireless communication, vision sensing, and coordinated control of multi-robots in the second and third parts of the sequence. To the authors' knowledge, this is the only such sequence in autonomous robotics that is being offered. The authors invite anyone interested in starting up similar courses to contact them via email.

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