Strategies and Outcomes in Robotics Education

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Abstract

Linked to the authors' 2004 ASEE Annual Conference CoEd workshop on Educational Robotics, this paper evaluates educational strategies and activities from the perspective of four engineering educators who have extensive first-hand experience in integrating robotics in the curriculum—from first year courses through senior design projects—and in assessing the educational impact of robotics projects and competitions. We show that one particular assignment, the development of autonomous mobile robots, ties together interdisciplinary design, experiential learning, teamwork assessment and other topical educational subjects in powerful and unique ways. We identify best practices taken from our experiences, focusing on (a) undergraduate experiences in fire-fighting robotics and in the AUVSI Intelligent Ground Vehicle Competition; (b) integrating robotics into the first year engineering design courses, advanced research project teams, and senior design projects; (c) robot design as a medium to promote teamwork; (d) methods of evaluation and assessment of robotics curricula and projects; and (e) recent trends in robot hardware and software for education.

Introduction

A robot is a mechatronic system that can be programmed to perform a range of mechanical and electrical functions and that responds to sensory input under automatic control. Robots can perform tasks normally ascribed to humans or animals, to imitate them and interact with them, or to act autonomously in various physical environments. Robotics is an interdisciplinary area that draws from such fields as engineering, physiology, and behavioral science. Robotic systems can be related to many physical processes and human practices in their interactions with the environment. The potential for using robots as educational tools for teaching and learning various subjects in technology, science, and humanities is unlimited.

Robotics is an especially effective medium for engineering education for many reasons, including the following:

- Engineering students acquire a holistic "mechatronic" view of electrical, mechanical and computer engineering, which enhances personal inclinations in these professional areas.
- Students acquire knowledge and experience that is important for their success in more advanced engineering courses and professional jobs after graduation.
- Students become involved in self-directed learning, interdisciplinary design, teamwork, professional communication, technical invention, and research.
- Students learn to investigate physical environments and human factors that determine engineering designs.
- Intensive practice in solving diverse mental and physical tasks in the robotics medium promotes development of student intelligence and creativity
- Robot design promotes the realization of ABET learning outcomes.

In this paper we consider these educational benefits as we describe best practices in robotics education gleaned from our accumulated experience in educational robotics. Our focus is to illustrate and describe curricular connections and sample courses including senior design projects and freshman engineering projects and to describe our assessment of success of educational robotics in curricular settings.

Undergraduate Robotics Education at Trinity College

Experiences at Trinity College indicates five main "effective practices" related to undergraduate education: (1) to motivate students through robot competitions; (2) to use robot design as the medium for an entry-level engineering course; (3) to use robot design as the foundation for team-based undergraduate research and design; (4) to use robotics to satisfy ABET learning outcomes. Each is considered below.

• Motivate students through robot competitions.

Trinity students and faculty have been engaged in autonomous mobile robot design since 1995, motivated in part by the opportunity to participate in two international competitions - the Trinity College Fire-Fighting Home Robot Contest (URL: http://www.trincoll.edu/events/robot/) and the AUVSI Intelligent Ground Vehicle Competition (URL: http://www.igvc.org/deploy/). Robots competing in the TCFFHRC must navigate through a maze and extinguish a candle in a race against the clock. In the contest's Expert Division, robots are presented with a different maze on each run, requiring generalized maze solving algorithms. In the Junior, High School, and Senior Divisions, the robots know the maze geometry in advance. The maze for these three divisions includes four rooms and connecting hallways (Figure 1). The candle is placed randomly in one of the four rooms, and the robot must navigate autonomously to within 30 cm. of the flame before putting it out.

The IGVC includes two main events, the Autonomous Challenge and the Navigation Challenge. In the Autonomous Challenge, robots navigate through an outdoor course, approximately 150m in length that is defined on each side by white lines painted on the grass. Robots aim to avoid such obstacles as traffic barrels and pails, and they must traverse sand traps and ramps. In the Navigation Challenge, robots navigate autonomously from a starting point to within one meter of nine different waypoints that lie on a grassy field approximately 125 m. on a side. Robots know the coordinates of these points and rely on GPS readings to determine position.

Such competitions provide to students many opportunities for learning, both in the robot design and preparation phase and in the competition itself. Specific learning outcomes related to contest participation for Trinity students include: (1) the ability to set design specifications based on contest rules; (2) the ability to work as team members; (3) the ability to perform independent study and research; (4) the ability to plan work and set deadlines; and (5) the opportunity to meet and to share ideas with competitors from other schools who have been engaged in solving the same design problem. Engaging students in competitions has emerged as a best practice.

• Adopt robot design as the medium for an entry-level engineering course.

Since 2000, the Trinity Engineering Department has offered an entry-level course ENGR 120 (Introduction to Engineering Design—Mobile Robotics, aimed at first-year students who are interested in the engineering major. ENGR 120 introduces students to the engineering field, informs them about the discipline and philosophy of design, and engages teams in a semester-long design project—development of an autonomous Lego-based fire-fighting robot (Fig. 1). Desired educational outcomes are 1) development of an awareness of the engineering profession, 2) development of communication skills, and

3) development of basic engineering skills through hands-on robot design. In 2003, 24 students (8 teams of three students) enrolled in the course. Each team was assigned a mentor, an undergraduate who has taken the course, who acted as team advisor and facilitator. Teams attended a one-hour weekly workshop that focused on robot design techniques, development of lab skills, and programming. The course used the text by Fred Martin [1]. Teams carried out several projects from the book including development of Braitenberg vehicles and wall following algorithms, to gain a general background in robotics required by the fire-fighting robot design problem. For more information about ENGR 120 the reader is referred to [2].

- Employ robotics as the medium for team-based undergraduate research and design.

Trinity undergraduate robotics R & D takes place within the Robotics Study Team (RST) that has included engineering and computer science students from all four college years. Students earn independent study credit for their work. The RST engages approximately ten students each semester. The RST is divided into project-specific groups; at the present time, one group is designing a fire-fighting robot to compete in the Expert Division of the TCFFHRC, and the second group is developing a new autonomous land vehicle ALVIN V that will compete in the 2004 IGVC.

The ALVIN project began in 2000, when a team of four engineering students developed ALVIN as a senior design project. ALVIN I was a four-wheel-drive vehicle that used a single camera to detect lines and an ultrasonic array to detect obstacles. An on-board Pentium III computer handled image processing, and a Motorola MC68HC332 performed data acquisition and motor control. Are-designed motor drive and transmission, and improved image processing algorithms, enabled ALVIN II to earn 6th place in the 2001 IGVC Autonomous Challenge.

A 2003 grant from National Instruments of LabView system development and image processing tools provided a comprehensive toolset for data acquisition, image processing, and motor control for ALVIN IV (Fig. 2). ALVIN IV employs two Firewire color cameras, an ultrasonic sonic sensor array, a digital compass, a sub-meter GPS and two computers for sensing and control - a 2.4 GHz P4 laptop for image acquisition, image processing, and path planning, and the Motorola MC68HC332 board for sensor input and motor control. The addition of a sub-meter GPS and LabView-based software enabled ALVIN IV to earn 6th place in the 2003 Navigation Challenge. Future plans focus on using distributed real-time LabView for data acquisition, motor control, and image processing.

- Use robotics as an educational vehicle to satisfy ABET learning outcomes.

A study reported in [3] indicated that robot design is a highly effective medium for realizing ABET core outcomes a-k. The study reported survey results of ENGR 120 students (N = 32) and nine RST students.

Data for ENGR 120 were derived from the standard course evaluation survey (SCE) that students complete at semester’s end for each course they take. As reported in [3], ENGR 120 students developed several core abilities through the course. The four areas of greatest reported impact were: (d) an ability to function on multi-disciplinary teams (4.85/5), (b) an ability to design and conduct experiments, as well as to analyze and interpret data (4.73/5), (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice (4.71/5), and (e) an ability to identify, formulate, and solve engineering problems (4.65/5). These high ratings result from experimental and design activities directly related to robot design and testing, and they are strong indicators of the merit of robotics as a medium for realizing the ABET outcomes. In addition to surveying the ABET a-k outcomes, the SCE asked students to evaluate their level of agreement with this statement: "The course has inspired me to continue my studies in this area." Of the 32 responding students, 25 responded with ratings of 4 (agree) or 5 (strongly agree), indicating that ENGR 120 motivated most students to continue with engineering studies.

The nine students taking the RST for credit in the fall semester of 2001 were asked to complete a survey form that asked them directly to rate the effectiveness of RST participation in meeting ABET outcomes a-k. As might be expected, juniors and seniors, the most experienced members of the team, reported a somewhat higher level of accomplishment than the first and second-year students. The strongest response areas for juniors and seniors were for (b) an ability to design and conduct experiments(5/5), (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice (4.8/5), (e) an ability to identify, formulate, and solve engineering problems (4.6/5), (a) ability to apply knowledge of mathematics, science, and engineering (4.6/5), and (c) an ability to design a system, component, or process to meet desired needs (4.6/5). Outcome g (communication skills) and outcome d (multi-disciplinary teams) also received strong responses (4.4/5).

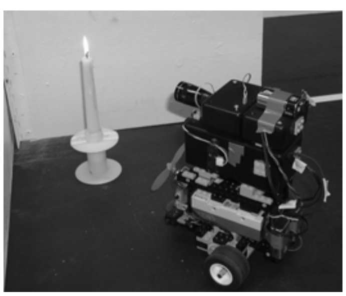


Fig. 1. Fire-Fighting Lego Robot.

Fig. 2. Autonomous Land Vehicle Alvin IV.

Evaluation and Assessment

A principal didactic problem of guiding projects in robotics is keeping the balance of two goals: (1) to create a working prototype capable to perform a robot contest assignment, and (2) to provide a systematic theoretical framework for understanding engineering subjects. Our studies [4, 5] indicated differences in the self-evaluation of experiences and learning outcomes of the robot project by students of different robot teams, and even within one team. We believe that this disparity can originate in project guidance differences, and that their optimization can afford more effective experiences and better outcomes. Therefore, identifying key concepts of the project and facilitating their learning by each of the team-members become essentially important parts of the project guidance.

Two of the authors have conducted formal evaluation of the TCFFHRC surveys since 1999 and reported on the results [5, 6]. The survey goals moved from a focus on general information and contestant feedback about their robot projects to analyzing and evaluating learning experiences and outcomes. The survey validity has been increased through the following actions:

- Increasing survey population by making it a part of the contest registration procedure,
- Comparing students' self-assessment and teachers' evaluation data,
- Using a subsequent survey to validate results of previous ones,
- Verifying survey findings by case studies of fire-fighting programs in different institutions.

In the 2003 contest survey we addressed separate forms to contestants of school divisions, senior and expert divisions, and to team supervisors. The form for junior and high school divisions included three sections: general, academic achievement, and work skill development. The general section requested for student's name, country, school, grade, team name, and form of participation in the project. The academic achievement section presented a list of disciplines, abilities, and skills and asked the student to estimate his/her progress in each of them due to robotics studies and participation in the fire-fighting robot project. The work skill development section listed main subsystems of a fire-fighting robot and asked the student to specify his/her contribution to development of each of the subsystems.

The form for seniors and experts consisted of the same three sections but was primarily focused on contestants who were university students and hobbyists. The form for supervisors included general, academic achievement, and instruction and assessment sections. In the academic achievement section supervisors were asked to estimate average progress of their students the same list of disciplines, skills and abilities as that given to seniors and experts. In the instruction and assessment section the supervisors described their instruction and assessment methods used for guiding the fire-fighting robot project.

Two hundred forty participants completed the 2003 contest survey forms, including133 contestants of the school divisions (55.4%), 82 of the senior and expert divisions (34.2%), and 25 supervisors and instructors (10.4%). Below we present salient educational features revealed by the 2003 survey, which were not treated by the previous surveys.

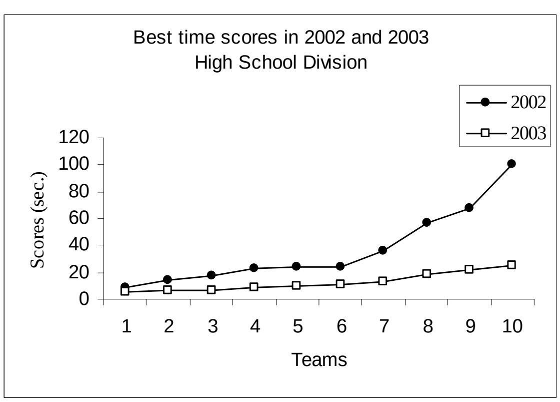
Progress in performing robot tasks

From year to year competition in the TCFFHRC has become more and more intense. The number of robots that succeed in extinguishing the fire increases each year, and the robots need less time to perform the task. This tendency is shown by Figure 3, which consists of two curves. The curves represent time scores of robots that won the first ten places at the 2002 and 2003 contests in the high school (Figure 3a) and senior (Figure 3b) divisions. As indicated by the diagrams, the 2003 scores in both divisions were better (lower) than in 2002, their range narrowed, and differences between neighboring places diminished. We consider this indication as an important argument for upgrading the 2004 TCFFHRC assignments.

Curricular vs. extracurricular projects

Previous surveys indicated that some student teams performed robot projects as part of their formal courses while other teams designed and built robots as extracurricular and hobby activities. With regard to these two forms of participation in the robot project we asked if they provide equal opportunities for teams to win the contest. This question is especially topical for the high school division, in which interest to win a contest is a more important motivation factor than in other divisions [4]. To

(a)



(b)

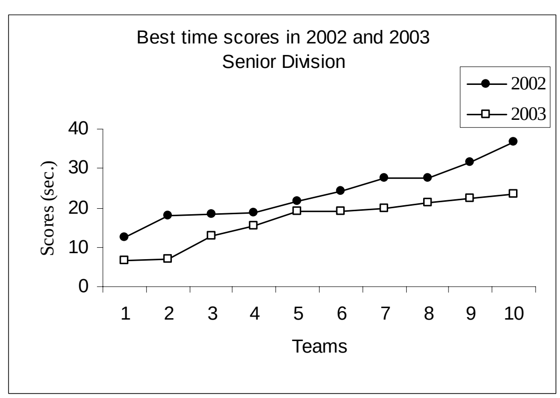


Fig. 3. Comparison of Top Ten Robot Scores, 2002-2003.

answer it we compared achievements in the 2003 contest for two groups of high school teams. Teams in the first group studied robotics in formal courses and in the second group through extracurricular activities. Data analysis indicated that contest achievements in the first group were significantly higher in the first group than in the second group ($P_{value}<0.05$). The percentage of robots, which successfully passed the contest qualification round, was significantly higher in the first group 85.2% than in the second group 55.5%. The authors plan to address these differences in the 2004 TCFFHRC.

Academic achievement

Previous surveys indicated that university and high school students positively evaluate their progress in theoretical and practical knowledge in a number of subjects due to their participation in the fire-fighting robot projects [7]. In the 2003 survey as in the previous surveys the absolute majority of students reported about their progress in electronics, computer communication, microprocessors, programming, mechanics, motors and gears, sensors and measurement, data analysis, control, and system design. In addition to progress in these subjects the 2003 survey evaluated students' advances in skills and attitude change. Skills and attitudes concerned in the survey were similar to that used in assessment of learning advancement in cooperative education [6].

The features indicated by the survey results are as follows:

- Almost all university and high school students reported on progress in their project skills, due to participation in the fire-fighting robot project. Half of them evaluated their progress as considerable.
- Many students in both divisions reported on their progress in general skills, but only 10-30% of them evaluated it as considerable. Part of the students did not mention any progress in general skills.
- The majority of the students evaluated the positive impact of the robot project on their learning motivation and interest to specialize in science and engineering. Lower progress was achieved in clarification of career goals and expectations.

Robot making

As shown by the previous surveys, the majority of university and high school students reported on their significant contributions to designing, constructing, testing, improving and installing subsystems of their robots. In the 2003 survey we observed differences in project experience and contribution among students of various teams in the high school and senior divisions. We found seven typical areas of contribution, which characterize student's experience in the project. They are listed in the first column of Table 1. The second and third columns present the percentage of students on the high school and senior division teams who contributed to each of the areas.

Table 1 indicates that the largest group of students in both divisions (about 40%) contributed to main robot subsystems by designing and building mechanical, electronic, and software components. Students from the second group (about 25%) contributed mainly to mechanical subsystems and electronic components. Their experience in software development was limited. In contrast, the third group of students (about 15%) contributed mainly to development of robot software and certain electronic and mechanical components. Their involvement in mechanical design and construction was limited. For the fourth group of students (about 10%) the main contribution was testing and improving subsystems, while the fifth group (about 4%) dealt only with sensor and control electronics. Contribution of students from the sixth and seventh groups was limited or not specified. The data in Table 1 support our belief that differences in project experience may determine student learning experiences in fire-fighting robotics and should

Table 1. Distribution of students according to their main contribution area (%).

	Contribution area	High school	University
1	Main robot subsystems	40.7	35.9
2	Mechanical subsystems and electronic components	25.2	23.4
3	Software subsystem, electronic and mechanical components	14.6	17.2
4	Focus on testing subsystems	9.8	10.9
5	Focus on sensor and control subsystems	3.3	4.7
6	Limited involvement	3.3	3.1
7	Not answered	3.3	4.7

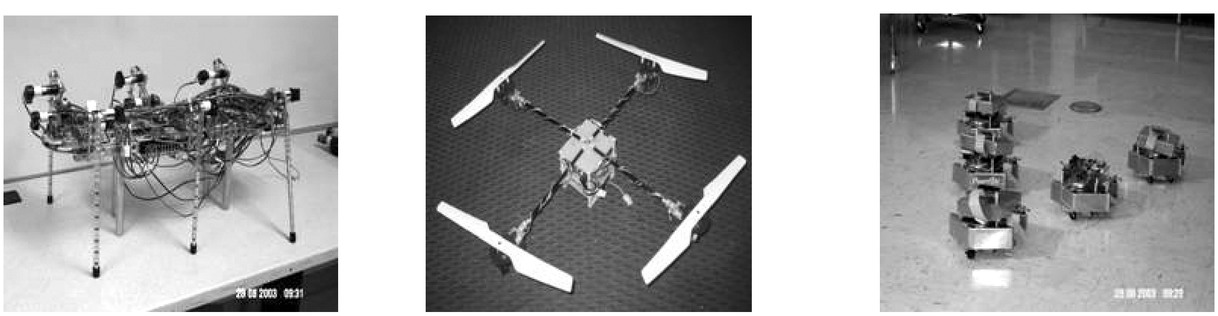
be addressed in assessments of learning outcomes. One issue to be addressed is how team organization affects learning and how best to organize teams to achieve the best learning outcomes.

Senior Design Projects

In this section, we present three examples of senior design robotics projects administered at the United States Air Force Academy (USAFA) over the past two years. We show that each of the three projects contains sufficient hardware and software design components for students to apply their accumulated knowledge and skills learned from the electrical engineering and the computer engineering undergraduate curricula. The order of our presentation is as follows. We first give brief descriptions of the three projects, followed by the motivations behind the selections of the projects. We then present how the projects are administered by faculty members and completed by students. We finally provide readers with some qualitative results and the lessons we learned from the three projects in the Discussion section.

Projects: The following three different projects were designed and performed in a two-semester senior design course: the walking robot project, the flying robot project, and the swarm mobile robot project. The objective of the walking robot project, shown in Figure 4a, is to design and create a hexapod with capabilities to maneuver on rough terrains. The objective of the second project, the flying robot project, is to design and construct a flying vehicle with hovering capabilities [8]. A photo of the project is shown in Figure 4b. The objective of the third robotics project is to design and construct seven mobile robots that can search for three ground targets located in an unknown area populated with obstacles and drop wooden cubes on the targets [9]. Students are completing the third project during the current academic year. Figure 4c shows a photo of robots created by another set of students during the past academic year.

Motivations: Projects based on robotics are ideal for a senior capstone design course since they provide ample opportunities for students to exercise skills and knowledge associated with (1) electrical/electronics engineering as students design, construct, and test SSI, MSI, and LSI circuits in sensors, devices, and control modules; (2) computer engineering as students



(a) Walking Robot (b) Flying Robot (c) Search Robots

Fig. 4. Three example robotics projects used in a senior design course.

work with microprocessors, microcontrollers, FPGAs, and DSP chips; (3) instrumentation engineering as students interface sensors, controllers, microprocessors, and power modules; (4) mechanical engineering as students design and construct mechanical components of robots; and (5) computer science as students program robot functional units using assembly programming languages, high level programming languages, and Hardware Descriptive Languages (HDLs). It is the responsibility of faculty mentors to balance the challenges students will encounter in a project with the knowledge and skills of the students already possess. Hence, the project selection should be determined based-on well-established criteria that reflect the senior design project objectives of a particular institution. A variety of robotics projects give faculty members the flexibilities desired to meet the objectives of an individual program.

Administrative Issues: We now briefly discuss the administrative portion of senior design projects. We present the method developed at USAFA in this section and share the lessons learned in the Discussion section. At USAFA, the senior design course for the electrical engineering and the computer engineering students is a one-year, two-semester long, course. We start the first semester with lessons to teach students hardware skills necessary to implement a complex project, such as design and manufacturing skills for custom designed boards with VLSI, LSI, MSI, and SSI devices, not covered in other required courses. Once hardware skills are acquired, students then learn skills to break down a big project in to multiple sub-tasks, to manage project progress, and to plan project activities from the start to the finish. They also have lessons on engineering ethics using case studies. Faculty members propose a variety of projects and students apply for projects of their interests. The project selection occurs in the middle of the first semester.

Once the project selection is determined, students are required to present a formal system requirement briefing based on the project description provided by faculty members. For example, the following is the project description for the flying robot.

> "The military is researching the possible use of robots to replace human intelligence assets. Robots with hovering capabilities can conduct close surveillance on a specific area for long periods of time. These robots will be required to maneuver indoors and remain in an area of interest. The smaller these robots are, the better chance they can perform their mission undetected. Additionally, a hovering robot can assist in combat theaters and explore distant planets. The final flying system, with the help of various sensors and a signal processing unit, will autonomously lift, land, and control its flight while avoiding obstacles."

Given the above project description, students, with the help of faculty members, came up with the following system requirements.

1. System must be autonomous
2. All electronic resources including power system must be on board
3. Must take off and land autonomously
4. Must maintain level flight
5. Robot must have capability to move in all three directions
6. Robot must avoid walls and obstacles
7. Robot must have capability to upgrade

<u>Constraints:</u>Use a Motorola 68HC12 controller

<u>Other Requirements</u>

1. Should not cost more than $700.00
2. All hardware must be rugged
3. Users Manual must be provided
4. Technical Report must be provided with sufficient detail to duplicate the system as well as test and repair it

Once the system requirements are accepted by both students and the mentors, the students then carry out the system design task. At this stage, students are responsible to acquire all hardware and software components that will satisfy system requirements. They have not implemented any of the project units, but must carry out trade studies and unit analysis. Once the system design is done, students now perform preliminary design task, where they implement and test individual modules of the project. For example, for the swam robot project, students designed and implemented a motor drive sub-module, a target detection sub-module, a wall and obstacle detection sub-module, a Liquid Crystal Display (LCD) module, a power sub-module, and a central controller module as a part of the preliminary design task. The semester ends with a formal briefing and students are required to turn in a technical report.

The entire second semester is used to integrate and test sub-modules to create the overall system. Students are responsible to meet some landmarks and provide faculty members with occasional formal briefings to update the progress of the project. The sample syllabi we use for the first semester and the second semester senior design course are included in the Appendix.

Current Trends in Instructional Robotics Systems

Some of the most visible and recent advances in applied robotics are driven by a highly goal-oriented approach to robotics development. The Rovers recently sent to Mars build on the previous successes of NASA's Pathfinder mission. These robots were designed entirely for a specific goal and that goal dictated most, if not all, of the design choices. With the Mars Rovers being a costly example of goal-oriented design, the Roomba vacuum cleaner robot is another recent addition that is a rudimentary and minimal robot design (URL http://www.irobot.com). The Roomba was designed with a specific goal in mind, sweeping the dust from a floor. Goal-oriented design is critical for project success in multi-discipline robotics engineering. So, how are people currently approaching the problem of designing a robot suited to a specific task such as putting out a candle?

Using robotics as the substrate for education often boils down to a multiple constraint problem with abilities, costs, time, and equipment being some of the most common constraints that students and instructional faculty need to address. In some ways, the interplay between these constraints when solving a real-world problem like the Trinity maze is a major component of the actual learning experience. While this constraint tension is a valuable learning experience, focusing too much energy on the constraints themselves can limit the absolute results of the team.

As pointed out in previous sections, students and teachers break down the experience in post-analysis into distinct disciplines and component systems and disciplines. Depending on the goals of the course, competition, and participating teams, it can be very advantageous to focus on a subset of these component pieces of the entire experience. Currently available and emerging resources greatly facilitate this form of focused learning. In some ways, this focus can improve the outcome of the course within a specific discipline or department and still benefit from the team interaction and proximity to allied disciplines.

Focused courses in robotics mirror the current trends in advanced robotics research. Decades ago, the researcher needed to build the entire mechanism, software tools, and associated electronics just to get started in robotics research. Current trends show emerging controllers, platforms, and software components that can often greatly accelerate the process of getting up and running toward the goals of the course. An added benefit of using component systems in robotics education is the tactile teaching of the interplay, interfaces, and limitations inherent in component systems.

A simple example of the component approach is the small IR rangers manufactured by Sharp Electronics. These small components completely encapsulate the process of using IR light to obtain short-range distance and obstacle information. These components didn't exist a decade ago and much of the effort involved in building a robot from scratch involved solving this problem with less than optimal solutions involving somewhat complicated electronic circuits and a handful of difficult to obtain parts. The small IR ranger component completely solves this problem at a cost (both in time and money) that allows the project to move much farther along yielding better results. Similar encapsulated sensors and actuators now exist for motion control, I/O manipulation, sonar ranging, speech synthesis, compass heading, flame detection, and other basic needs of mobile robots.

Another common component that often proves to be a stumbling point for teams is the actual mechanical system of a robot. As a multi-discipline course, robotics can be offered by departments and facilities that do not have a full machine shop for fabricating a specific design or mechanism. This is especially true of high school groups or faculty not in physical engineering disciplines. A Computer Science faculty member interested in educating and teaching basic algorithms using robotics likely doesn't have machine shop and may never have even soldered a wire! There are now very capable complete robot platforms like the Garcia robot that alleviate this problem, allowing the students and team to begin with a known and reliable quantity, building out with software and sensing as needed by the goals set out by the course.

Completely focusing on a single discipline can be a detriment to the overall team experience as seen in some of the FIRST designs and in talking with many participating teams. These robots and the structure of these competitions tend to nearly completely remove the issues of electronics and software. They become strictly mechanical puppets that require vast mechanical engineering resources. The student time spent in these projects can result in more of a fund-raising exercise than an engineering lesson. At the same time, the wheel is often re-invented (literally) over and over again in robotics education, which limits the overall capabilities of the resulting robots. Much greater progress towards the goals of a course is achieved when picking specific sub-systems to focus on while relying on existing and emerging sub-components.

In summary, the current trend of educational robotics follows the general trend of robotics. Component systems, focused research or applications, and generally more accessible components, information, and opportunities are pushing the quality and complexity of the robots being built by teams of young first-time students. Better, more capable robots allow more focus on behavior and expression, which has proven to attract even more student interest [10]. In some ways the course goals and actual design of the course competitions need to evolve along with the robots to remain challenging and offer a rich, unbounded learning substrate.

Discussion

Due to the limited space, we only present some qualitative results and key lessons we learned. For a complete presentation, we invite readers to the workshop and refer them to our future papers.

Effective practices in undergraduate education at Trinity College: Four effective practices involving robotics as a medium for undergraduate education have been described in this paper: to (1) motivate students through robot competitions, (2) adopt robot design as the medium for an entry-level engineering course, (3) employ robotics as the medium for team-based undergraduate research and design, and (4) use robotics as an educational vehicle to satisfy ABET learning outcomes. Practices 1-3 have helped to build a project-based research and development environment at Trinity College in which students work as teams, carry out research, and create working autonomous robots that compete against other universities' robots. As practices 1-3 focus on an interdisciplinary team-oriented high-tech design project, they implicitly lead to (4), realization of ABET outcomes.

Evaluation and assessment results: Our study highlighted the need for increasing the level of challenge in the robot competition. We recommend that instructors focus on developing integrative skills among their robotics students and challenge them to conceptualize knowledge acquired through practical experience in the projects. Teachers also need to balance time devoted to developing hands-on skills with attention to developing a strong theoretical framework. We note the strong indication, from our data, of the contest's general success in promoting engineering education, both at the high school and undergraduate level.

Lessons learned from senior design projects: A single student performed the walking robot project. At the end of the project, the student created and tested hardware and software components for individual legs but ran out of time to integrate the entire system. The flying robot project was also performed by a single student. At the end of the course, the flying robot demonstrated minimal flying capabilities. The main difficulty of the project was less than accurate sensor data from on-board gyros. During the current academic year, two six-member teams are working on the swarm robot project. Both teams have successfully completed all steps required at the end of the first semester. We plan to report the full project results at the conference. Some key lessons we learned are: (1) provide students with ample opportunities to practice breaking down and scheduling tasks involved with a complex project; (2) hold a weekly meeting with the mentors is a must; (3) create multiple sub goals for students to reach throughout the course; (4) look for any disharmony in a team and remedy the situation quickly; (5) hold each member of a team accountable for his or her task by specifying the responsibilities of each team member; (6) enforce a weekly student team meeting before meeting with the faculty mentors; (7) find the critical balance between proper guidance and allowing students to be creative; and (8) form a team of mentors with wide expertise to help students in different aspects of projects.

We conclude that robotics education is an extremely effective means of introducing systems thinking, cross-disciplinary learning, teamwork, and project management skills. Effective courses can be structured around a specific goal, contest, or challenge that allow the students to freely create and investigate challenging and nearly unbounded engineering design problems in the robotics domain. Current trends and advances will improve the capabilities of both students and their robots. Robotics education has been shown in both short and long term studies [10] to encourage students to pursue engineering and to give students practical tools for future engineering successes.

Bibliography

1. F. Martin. "Robotic Explorations, a Hands-On Introduction to Engineering." Prentice-Hall, 2001.

2. D. J. Ahlgren. "Fire-Fighting Robots and First-Year Engineering Design: Trinity College Experience." Proc. at the ASEE/IEEE Frontiers in Education Conference, Reno, NV, October, 2001.

3. D. J. Ahlgren. "Meeting Educational Objectives and Outcomes through Robotics Education," Proc. 2002 World Automation Conference, Orlando.

4. I. Verner, E. Hershko. "School Graduation Project in Robot Design: A Case Study of Team Learning Experiences and Outcomes." Journal of Technology Education, 14(2), 2003.

5. I. Verner, D. Ahlgren. "Fire-Fighting Robot Contest: Interdisciplinary Design Curricula in College and High School." ASEE J. Engineering Education, July 2002.

6. D. Ahlgren, I. Verner. "An International View of Robotics as an Educational Medium." Presented at the 2002 International Conference on Engineering Education, Manchester, England, August 2001.

7. D. J. Pack, R. Avanzato, D. J. Ahlgren and I. M. Verner. "Fire-Fighting Mobile Robotics and Interdisciplinary Design-Comparative Perspectives." To appear in IEEE Trans. on Education.

8. J. P. Perlin, D.J. Pack, B.E. Mullins, and R.E. Speakman, "Senior Capstone Design Experience: Hovering Robot," Proc. of the 2003 ASEE Conference, Nashville, TN, June, 2003.

9. D.J. Pack and B.E. Mullins, "Toward Finding an Universal Search Algorithm for Swarm Robots," *Proceedings 2003 IEEE/RJS Conference on Intelligent Robotic Systems (IROS)*, Las Vegas, Nevada, October 2003.

10. T. Hsiu, S. Richards, A. Bhave, A. Perez-Bergquist, I. Nourbakhsh. "Designing a Low-cost, Expressive Educational Robot." In Proceedings of IROS 2003, Las Vegas.

Biographical Information

David J. Ahlgren is Karl W. Hallden Professor of Engineering at Trinity College, and he is Director and Host of the Trinity College Fire-Fighting Home Robot Contest. He joined the Trinity faculty in 1973 and served as department chair from 1990-1999. His interests include robotics, modeling and simulation, and broadband communications amplifiers. Dr. Ahlgren holds the Ph.D. in E.E. from The University of Michigan, Ann Arbor.

Igor M. Verner is a Senior Lecturer of Technology Education at the Technion - Israel institute of Technology. He received the M.S. degree in mathematics from Ural State University and a Ph.D. in CAD in manufacturing in 1981, at the Ural Polytechnical Institute, Sverdlovsk, Russia. His research interests include learning through designing, constructing and operating robot systems, and conceptual understanding in science-technology education.

Daniel J. Pack is Professor of Electrical Engineering at the United States Air Force Academy, CO. He is a member of Eta Kappa Nu, Tau Beta Pi (faculty advisor), IEEE (Senior Member), and ASEE. He is a registered Professional Engineer in Colorado, and was a visiting scholar at Massachusetts Institute of Technology-Lincoln Laboratory. He received the Ph.D. degree in Electrical Engineering from Purdue University.

Steve Richards is the Founder and President of Acroname Inc., a leading company dedicated to robotics research, education, design, and providing access to the highest quality components. He received the B.S. in Computer Science in 1990 and the M.A. in Mathematics in 1990 from the University of Oregon. His research interests include mapping, rigid-body simulation, controller architectures, and human factors design issues.

Appendix

This syllabus is used in the first semester senior design course at the United States Air Force Academy.

Lesson	Topic	Meet In Class	Assignment	Notes
1	Intro, Admin, PCB Layout Overview	✓	Read PCB Handout	
2	PCB Footprints, PSPICE Schematic Preparation	✓	PCB Terminology Quiz	
3	Custom Schematic Parts, Netlisting for Layout	✓	Due: Schematic Preparation Exercise	
4	Creating PCBs, PCB Design	✓	Due: Layout Schematic and Netlist File Exercise	
5	PCB Autorouting and Modification	✓	Due: PCB Design Exercise I	
6	PCB Finishing	✓	Due: PCB Design Exercise II	
7	Methods 1: PCB Design for Noise Suppression	✓	Due: Practice PCB Circuit	
8	Methods 2: Methods for Signal Transmission	✓	Due: PCB Design Problem	
9	Methods 3: Logic to System Interfacing	✓	Due: Signal Transmission Exercise	
10	Methods 4: Timers and Oscillators	✓	Due: Interface Design Exercise	
11	Methods 5: Power Supplies and Voltage Regulators	✓	Due: Oscillator Exercise	
12	Project Briefings	✓		
13	Chassis Design for Ground Safety and Noise Suppression	✓	Due: Power Supply Design Exercise	
14	Electrical System Noise Reduction Methods	✓	Due: Chassis Safety Exercise	
15	Graded Review	✓	Read Case Study Prepare Summary	
16	Ethics Case Study	✓	Due: Case Study Summary	(continued)
17	Design Process I	✓	Due: Ethics Case Study Paper Due: Project preferences	

18	Design Process II	✓		
19	Project Estimating and Planning 1	✓		Project Notification
20	Project Estimating and Planning 2	✓	Due: Draft Project Schedule	
21	Technical Writing for Project Design	✓	Due: Project Estimation Exercise	
22 - 23	Systems Requirements Review Preparation (5-Hours)	NO	Due Lesson 22: Writing Exercise	
24	Systems Requirements Review	NO		FORMAL BRIEFING
25 - 31	Initial Design Development (17.5Hrs)	NO		
32	Initial Design Review – Finalize Prototyping Requirements for PDR	NO		FORMAL BRIEFING
33	System Test Methodologies	✓		
34 - 41	Preliminary Design Development (25 Hrs)	NO	Due Lesson 36: Draft Integration Test Plan Due Lesson 42: First Draft Technical Report	
42	Preliminary Design Review – Decision for Full Scale Development	N/A	DUE: PDR Briefing and prototype hardware demo	FORMAL BRIEFING

The syllabus used in the second semester senior design course at the United States Air Force Academy:

Lesson	**Activity/Milestone**
Lesson 1	Attend Class - Administration Out of class: Your team needs to contact the project mentor to set up weekly meetings. Your Project Manager will meet with your team lesson 1 or 2, to revise and refine your project schedule.
Lesson 3	*Attend Class – meet in EE 322 lab* - Take the "Laboratory Skills Assessment"
Lesson 12	Turn in Technical Report--Second Draft
Lesson 19	Last day to complete CDR - Final design complete and working prototype demonstrated - *Must be completed by COB 4 Mar 04*
Lesson 22	*Attend Class* - Take the "Electrical Engineering Climate Survey"
Lesson 30	*Turn in Technical Report--Third Draft (includes final System Test Plan)* - *Due by COB 12 Apr 04*
Lesson 41	*Last day to complete Acceptance Test*