Integration of a Fire-Fighting Robot Contest in Multi-Level Engineering Education

David J. Ahlgren, Igor M. Verner
Trinity College/Technion—Israel Institute of Technology

Abstract

This paper examines the educational benefits of the Trinity College Fire-Fighting Home Robot Contest and it describes contest-related curricular developments, both at university and high-school levels, that have been sponsored by Trinity College and the Technion—Israel Institute of Technology. The paper evaluates the value of the contest as a medium for team-based interdisciplinary design. Our findings are based on analysis of specific curricula as well as assessment surveys carried out at the 1999 and 2000 fire-fighting competitions.

I. Introduction

Traditional approaches to engineering curriculum and instruction are being changed in response to current and anticipated priorities in cross-disciplinary linkages, systems approaches, and project-oriented learning in interdisciplinary teams. This emphasis is evident in the EC2000 criteria published by the Accreditation Board for Engineering and Technology [1]. Under the EC2000 model, engineering programs are evaluated by assessing success in meeting stated educational outcomes, including ABET's basic outcomes a – k.

One ABET outcome, the "recognition of the need for, and an ability to engage in life-long learning [1]," can be met by engineering programs that offer, in addition to formal courses and laboratories, "co-curricular" activities outside the classroom. One co-curricular activity, participation in robot design competitions, is being pursued by a growing number of universities, colleges, and even secondary schools. For example, over the last seven years, hundreds of students from universities, high-schools, and junior high schools have participated, via this co-curricular model, in the Trinity College Fire-Fighting Home Robot Contest (TCF^2HRC).

We show, in this paper, that the contest has inspired curricular development at all educational levels while offering the opportunity for educators from around the world to compare contest-oriented curricula they have generated. Because robot design is an interdisciplinary process, contest-oriented curricula share a "threaded" approach in which the primary assignment--to develop an optimal robot for the competition -- is declared as the general goal of the curriculum. This goal threads knowledge and skills through the various disciplines taught in the course, creating a purposeful, project based learning process.

The paper presents experiences of the authors in developing robotics curricula at undergraduate college and high-school levels. We compare contest-related curricula, learning subjects, robot designs, and learning outcomes. Our assessment is based on educational surveys developed by the authors and administered at the 1999 and 2000 fire-fighting contests at Trinity College.

II. Trinity College Fire-Fighting Home Robot Contest

Dozens of robot contests announced on the Internet relate to different levels of engineering education and can be classified in three groups [2]: entry level, intermediate level, and advanced level. In the entry-level robot contest students participate without engineering background. A fixed time period and assistance from professional engineers are assigned to teams to design and build from a standard kit a remote controlled robot able to play a specific game (e.g. the Sumo game). Then the students compete against other teams by operating the robots manually. A competition called FIRST (For Inspiration and Recognition of Science and Technology) [3] presents an example of an entry-level competition aimed at raising excitement about science and engineering among high school students.

In one advanced-level robot competition, interdisciplinary scholarly teams develop robots, built on the autonomous agent methodology, that exhibit reactive, adaptive, and collective behavior patterns. The primary goal of these contests is to foster research and development in robotics and artificial intelligence. Usually these contests coincide with prominent scientific forums. The robot soccer competition RoboCup [4] is an example of an advanced-level contest.

Intermediate-level competitions have become popular in undergraduate engineering education. In a typical intermediate-level contest, teams design and build autonomous robots that are programmed to perform specific intelligent functions. The robot operates in an invariable, partially defined environment, and the competition is judged on performance. The Trinity College Fire Fighting Robot Contest (TCF^2HRC) [5-7] is an example of an intermediate-level competition. The common task for all teams is to build a robot that navigates autonomously through a maze, detects a fire (a lit candle), and extinguishes the candle in the shortest time. The maze, which has four rooms and connecting hallways, represents the first floor of a house. The reader is referred to the Web site www.trincoll.edu/events/robot/ for the full description of the contest and its rules.

Since its founding in 1994, the Trinity College Fire-Fighting Home Robot Contest has become a popular international event. The contest has attracted college professors, university students, school pupils, unaffiliated inventors, and hobbyists. The event has been described in such publications as *IEEE Robotics and Automation Society Magazine, Electronic Design, Popular Mechanics, Byte,* the *London Times, Scientific American, Circuit Cellar Ink*, and the *New York Times.* The contest has grown internationally through regional affiliated contests that use the standard TCF^2HRC rules. In 2000, regional contests were held in Philadelphia, Fort Worth, Los Angeles, Seattle, Shanghai, Calgary, and Tel Aviv.

While engaging university and high-school students from a wide geographical area, the contest has provided an ideal medium for introducing under-represented female and minority Hartford-area high-school teams to the field of engineering. Through the United Technologies Trinity College Engineering Initiative (UTCEI) high-school student have worked on research teams that include Trinity faculty and undergraduates. A significant number of high-school students have developed fire-fighting robots and have participated in the TCF^2HRC [8].

Given this increased popularity of robot competitions in engineering education, it is appropriate to evaluate the integration of the contest in the curriculum and to carry out an authentic assessment of the learning outcomes.

III. Education Through Interdisciplinary Design

This section discusses our understanding of education through the interdisciplinary design of sophisticated, autonomous mobile robots to compete in the TCF^2HRC. Through development of an autonomous mobile robot and participation in the fire-fighting contest, students inherently realize several of the ABET EC2000 educational outcomes a-k [1]. Our discussion here focuses on outcome (c), "An ability to design a system, component, or process to meet desired needs," and outcome (d), "An ability to function on multi-disciplinary teams."

In fact, the educational benefits of designing an autonomous fire-fighting robot extend beyond the ABET outcomes and include the following:

1. Individual students and design teams develop and accumulate knowledge and skills in high-tech electrical, mechanical, and computer engineering areas that are in high demand in industry.
2. Many techniques and tools useful to scientists are studied and applied in the course of inventing and building a mobile robot. These include sensing and communication devices, feedback control theory, and methods of navigation and obstacle avoidance.
3. The contest provides a focused, open-ended, interdisciplinary project that is a strong motivator of student creativity, self-directed learning, and research. As students strive to build the optimal fire-fighting robot, they work creatively, learn as individuals, and learn as members of a team.
4. Through cooperation and the development of professional relationships within and beyond the contest community, students develop and strengthen their teamwork and communication skills.
5. Students become keen on designing robots and they enjoy participating in the contest.

In our view, the key to a successful interdisciplinary design experience is the formulation of a significant design problem that inherently requires solution from more than one perspective. The problem must be challenging and of sufficient complexity and magnitude to require the concurrent, creative efforts of several design team members. The project should generate new design problems as old ones are solved, offering opportunities for research and development by future teams in an open-ended fashion.

In engineering corporations, each member of a team brings specific expertise to the design process. In the university setting, the interdisciplinary team may include students from different major fields and with different skill levels. On such teams, the experienced, more skillful students take active roles in educating those with less experience.

The fire-fighting robot design problem presented by the TCF^2HRC measures up to these criteria. Most of the robots competing in the TCF^2HRC are the products of engineering design teams; fully one-half of the university teams that competed in the 2000 TCF^2HRC developed their robots as part of a senior engineering design project. Over the years, the contest has inspired more than fifteen senior design projects at Trinity College. We note that high school science teachers from the U.S., Canada, and Israel have chosen the fire-fighting robot problem as the topic for graduation projects that develop teamwork skills and promote university-level engagement in science and engineering.

Specific contest-related curricula developed at Trinity College and Technion are considered in sections IV and V.

IV. Curricular Models: Experience at Trinity College

Since its beginning in 1994, the TCF^2HRC has encouraged development and continual improvement of the robotics curriculum at Trinity College. Engagement of Trinity engineering and computer science students in robot design, testing, and competition has brought the varied interests of students and faculty to bear on solving a series of open-ended, never-ending design problems in a team setting. For many of these students, the development of successful autonomous fire-fighting mobile robots and competing with them in the contest is the most engaging experience of their undergraduate years.

The TCF^2HRC has had significant impact on three areas of the Trinity engineering curriculum: (1) an engineering design course aimed at first-year prospective majors; (2) senior design projects, and (3) team seminars focusing on mobile robotics. Each of these is described below and illustrated by examples. All three emphasize communication and demonstration of results through oral and written reports and by participating in the TCF^2HRC.

First-Year Engineering Design Course

The Trinity College course ENGR 120 (Introduction to Engineering Design -- Mobile Robotics) was offered in spring, 2000 and will be offered again in spring, 2001. In 2000, the 21 students in ENGR 120 were divided, at random, into seven teams of three. Each team created a fire-fighting mobile robot based on Legos and the Handy Board, a small MC68HC11-based system designed for educational robotics and research [9]. The manuscript of a new book by Fred Martin, "Robotic Explorations, a Hands-On Introduction to Engineering [10], was an essential information source for the team projects.

Stated skill development areas for ENGR 120 included the following: robotics fundamentals, software development using Interactive C, basic use of laboratory instruments (oscilloscope, signal generator, voltmeter), use of CAD packages for mechanical and electrical design, data acquisition, data analysis using Excel, digital logic basics, motor control (PWM, PD/PID, fuzzy logic), basics of microcontroller interfacing (A/D, parallel port), and development and use of sensors for ranging and flame detection. The course also provides practical, hands-on experiences with electrical and mechanical construction, cabling, soldering, and other technical skills.

Robotics Team

Students interested in more advanced robotics studies join the Trinity Robot Study Team, whose members design robots for competition. The seminar encourages the team to tackle open-ended research and development problems. Team members enroll for independent study credit, which can vary from one semester hour to three semester hours per term. The team is sectioned into four design groups--mechanical, electrical, software, and sensors. Each group gives a progress report during the team's weekly seminar. The seminar offers students an interdisciplinary, team-based design setting that few other environments outside of industry can offer.

Because it includes students from all four college years, the team naturally grows a tiered learning and mentoring structure in which the experienced students are mentors, and where the team grows collective expertise. As the team strengthens its knowledge base it attacks more difficult problems (e.g. vision system design and walking robot design). The team's management structure consists of the chief engineer (a senior engineering major), the student leaders of the mechanical, electrical, software, and sensor design groups, and the faculty advisor. The chief engineer and leaders comprise a management committee that makes major decisions for the group. Another student serves as the librarian, whose primary role is to maintain documentation and software libraries.

Senior Design Projects

Many of the university teams that have competed in the TCF^2HRC have developed robots as part of the senior design experience. One-half of the robots entered by university teams in 2000 were associated with senior design projects.

For example, the contest has encouraged some fifteen senior design projects at Trinity during the last few years. These include the following: 1) capacitive proximity sensor with custom ASIC; 2) microcontroller to DSP interface; 3) servo controller for velocity stabilization of DC motors; 4) vision system for mobile robotics; 5) ultrasonic sensing system for obstacle avoidance; 6)

ALVIN, autonomous land vehicle; 7) FIRE, the fuzzy infrared robotic explorer; and 8) CMOS imaging system.

Fire-fighting autonomous robot design has also served as the theme for graduation projects for advanced high-school science students in several countries. One example is presented in the next section.

V. A Model for Design and Technology Instruction in High Schools

Since the 1998-99 school year high-school students in Israel have participated in TCF^2HRC and in the local fire-fighting robot contest organized by the Israeli Ministry of Education. The Israel delegation at the TCF^2HRC included 24 students from five schools in 1999 and 73 students from seven schools in 2000.

This experience serves as an impressive example of how to integrate robotics into the high-school curriculum with the support of the national school system [11]. In Israel, robotics is taught in high schools in the framework of the Machine Control discipline.

The Machine Control discipline was implemented in 1990, as part of technological education reform in Israel. The principal goal of this reform was to remove the total separation between comprehensive and technological schools and to create a common educational framework, with two clusters of school matriculation subjects: general subjects (obligatory for all students), and optional (majoring) matriculation subjects, which students choose out of a given cluster. Machine Control is included in the cluster of optional matriculation subjects. Moreover, this discipline has been authorized and accredited as one of six main disciplines preferred by the Israeli universities among the matriculation subjects.

The Machine Control discipline is studied in the eleventh and twelfth grades. It includes three subjects:

- Logic in Automated Control Systems at grade 11,
- Applications of Computerized Control at grade 12,
- Machine Control Workshop at grade 12.

Higher achievers have a privilege to prepare an advanced graduation project in grades 11 and 12. Each graduation project passes external assessment by the Ministry of Education as a substitute of the national exams in the three subjects of Machine Control. In the project the student implements some creative assignment in design and technology of Machine Control and documents the project results in the form of a R&D report. A more detailed description of the discipline is given in [12].

Many graduation projects in Machine Control prepared last three years relate to designing, constructing and operating robot systems. Such projects are based on creative work determined by a general goal of building a robot system that implements specific predefined intelligent functions. Examples of project assignments include: an autonomous robot for climbing up on walls and solving spatial puzzles by means of a robot-manipulator.

Robotics projects in high schools may consist of the following hierarchy of learning activities:

- Practice in task planning and performing manipulations by the robot;
- Implementation of sensing, control and communication functions for the robot system;
- Design of electrical, mechanical, computer and other modules for constructing the robot;
- Learning technology and science subjects needed to carry out the creative assignments.

Topics in electronics, computers, mechanics, control, as well as in physics and mathematics are added to the conventional syllabus of Machine Control as necessary to enable robot design and operation.

A growing number of high schools are now developing curricula and carrying out projects related to the fire-fighting contest. As an example, we will consider a fire-fighting robot project, which is been carried out at the Meviot Eron high school. The Machine Control discipline in this rural school has been taught since 1990 with a series of graduation projects related to the automatic control of a greenhouse based on programmable logic controllers.

In 1998 one of the teachers, Eyal Hershko, started his graduate studies at the Technion and majored in educational robotics under the guidance Dr. Verner. He has developed a fire-fighting project in his school since 1999, with Dr. Verner serving as project consultant. The Meviot Eron robot team participated in the 2000 local fire-fighting contest (3rd place) and in the TCF^2HRC 2000 (shared places 12 to 16).

The study of TalrickTM and Rug WarriorTM robot kits, the user manuals and the book [13] was an important initial step of the project activities. This experience helped the teacher and the students to acquire knowledge on movable robot systems, recognize problems to be solved and develop their own fire-fighting robot.

The robot team in 1999-2000 consisted of 13 students. The team was divided into five groups: structure, sensors, fire extinction, software and management. The structure group designed and built the robot structure, considering carefully the location of the center of gravity and the need to reduce robot weight. The sensors group dealt with calibration of sensors and real motors, and with the kinematics of robot straight and circular motion. The fire extinction group examined several possible solutions for extinguishing candles, chose a suitable propeller device, and mounted and tested it on the robot. The software group dealt with maze navigation logic and programming robot movements. The management group coordinated the project schedule, logistics, reports, and presentations.

The robotics project at Meviot Eron was studied with a view to the value of contest-oriented curricula and methods of interdisciplinary design education. As a result of the study several improvements were made in the curriculum of 2000-2001 currently in progress. The team is divided into 2 groups of equivalent amount of project work and responsibilities: structure and fire extinction (S&FE), and sensors and software (S&S). The S&FE group examines a number of alternative variants of the robot structure and fire extinction by means of physical and mathematical modeling, and CAD. The S&S group deals with robot XY kinematics, application of shaft encoders for the position control, and algorithms and software for maze navigation as required by new TCF^2HRC 2001 rules.

Important data for assessing learning outcomes of the robotics project at Meviot Eron, Trinity College and other institutions were provided by the contest surveys. A summary of findings from the 2000 contest survey and references to other related publications are given in section VI.

VI. Assessment Surveys

The Trinity College experiences at the undergraduate level and the Technion-sponsored high-school programs are representative of contest-related curricular developments at many other schools. To obtain a general assessment of contest-oriented curricula and general educational objectives, we developed a survey study that was administered at the 1999 and 2000 fire-fighting contests at Trinity. At each survey cycle our questionnaire asked team-members to provide details about their participation in the contest. An incremental survey method was applied in which the 2000 survey cycle validated results of the 1999 cycle and added knowledge to that previously found.

We focus here on findings from the 2000 survey that extend the 1999 survey results [14] related to one of the survey aspects, interdisciplinary design. The 2000 survey questionnaire asked each respondent to estimate his/her progress in a number of fields gained as a result of working on the contest project. The list specified 17 main fields of study students would encounter in a contest-oriented curriculum (electronics, computer communication, microprocessors, assembly language, high-level language, motors and gears, mechanical design, robot kinematics, sensors and measurement, data analysis, physical field concepts, mathematical modeling, control systems, CAD tools, systems design, robot programming, and teamwork). For each field the respondents evaluated their progress in theoretical and practical knowledge. The following features are revealed by the answers:

1. Most of respondents found that their contest-oriented curricula related to all 17 fields.
2. In most fields the majority of respondents considered their progress to be either considerable or extensive.
3. Such progress takes place both in theoretical and practical studies.
4. The progress in teamwork of the high school and university students is significantly higher than of the junior school students and engineers.
5. The university students achieved higher progress in electronics, computer communication, microprocessors, and sensors and measurement. They had lower level progress in high-level language programming, mechanical design, and physical field concepts.

Other section of the questionnaire asked respondents to describe their own activities in main project-related subjects (drive mechanism, mechanical structure, control circuits, micro-controller, sensor system, steering planning, extinguishing device, system software and other subjects (to be specified). For each subject respondents were asked to specify their involvement in various types of activities (adapting, constructing, designing, improving and integrating).

Some our findings from the answers:

1. Contestants from all four groups were involved in extensive practical work with robot systems.
2. 40-80 % of the university students were involved in each of the five types of activities, with more attention (on the average) occupied to integration and design of the robot components.
3. University students spent most of their effort working on the extinguishing device, the sensor system, the mechanical structure, the drive mechanism, and the system software.
4. University students were involved in the practical activities less than engineers but more than high school students. The lowest involvement with practical activities was in the group of junior school students.

VII. Summary

It is clear from the survey results that the TCF^2HRC has motivated and excited university-level and high school students as well as professional engineers and hobbyists. The contest has encouraged development of specific theoretical and practical technical skills, and it has provided significant opportunities for interdisciplinary teamwork. The TCF^2HRC has stimulated the development of new courses, seminars, and projects. The contest outcomes are consistent with ABET EC2000 criteria and new school standards for technological literacy. These are very positive findings.

The contest may not appeal to every student. Some prefer less competitive learning environments, and some may not stay interested in robotics. Moreover, the contest project should be considered a supplement to, and not a substitute for, formal engineering studies. Finally, the authors note the need for continual assessment of the contest itself and of the learning outcomes achieved by contest participants.

The TCF^{2}HRC presents a challenging, truly open-ended design problem that is never solved completely; with every robot there is room for improvement. Engagement with the TCF^{2}HRC offers students opportunities to meet, in an atmosphere of cooperative learning, others with similar interests from around the world. These benefits are experienced by university undergraduates and high school students from schools that have integrated the fire-fighting robot contest in the curriculum.

VIII. Acknowledgements

The authors recognize the many contributions of Jacob E. Mendelssohn, founder and coordinator of the TCF^{2}HRC. We also thank the many sponsors of the contest including Motorola Semiconductor Products Sector, Watts Industries, the National Collegiate Inventors and Innovators Alliance, and Charles L. Wilson III.

IX. Bibliography

[1] "Engineering criteria 2000 third edition," in Criteria for Accrediting Programs in Engineering in the United States. Baltimore, MD: The Accreditation Board for Engineering and Technology (ABET), pp. 32-34.
[2] Verner, I., & Waks, S. Educational Features of Robot Contests: The RoboCup'98 Survey. Advanced Robotics, 14(1), 65-74 (2000).
[3] URL: http://www.usfirst.org
[4] URL: http://www.robocup.org
[5] Ahlgren, D. & Mendelssohn, J. The Trinity College Fire Fighting Home Robot Contest. Proc. ASEE Annual Conference, Seattle (1998).
[6] Avanzato, R. Collaborative Mobile Robot Design in an Introductory Programming Course for Engineers. Proc. ASEE Annual Conference, Seattle (1998).
[7] Pack. D., Mankowski, A. M., and Freeman, G. J. A Fire-Fighting Robot and its Impact on Educational Outcomes. Proc. ASEE Annual Conference, Seattle (1998).
[8] Broadbridge C. & Stoane, D. The United Technologies/Trinity College Engineering Initiative (UTCEI): A Proven Model for the Accretion and Retention of Women and Minorities in the Fields of Engineering and Science. Proc. 1999 Frontiers in Education Conference, San Juan.
[9] URL: http://www.handyboard.com
[10] Martin, F. Robotic Explorations, a Hands-On Introduction to Engineering. Prentice Hall, 2001.
[11] Verner, I., Waks, S., & Kolberg, E. Upgrading technology towards the status of high school matriculation subject: A case study. Journal of Technology Education, 9(1), 1997, pp. 64-75.
[12] Verner, I., & Betzer, N. Machine Control - A Design and Technology Discipline in Israel's Senior High Schools. International Journal of Technology and Design Education (in press).
[13] Jones, J., Seiger, B., & Flynn, A. Mobile Robots, Inspiration to Implementation, 2nd ed. A. K. Peters, (1999).
[14] Verner, I., Ahlgren, D., Mendelssohn, J. Fire-Fighting Robot Competitions and Learning Outcomes: A Quantitative Assessment. Proc. ASEE Annual Conference, St. Louis (2000).

DAVID J. AHLGREN
David J. Ahlgren joined the Trinity College faculty in 1973 and is Professor of Engineering. He received the B.S. in Engineering from Trinity, the M.S. in E.E. from Tulane University, and the Ph.D. in E. E. from The University of

Michigan, Ann Arbor. From 1990-1999 he was Chair of the Trinity College Department of Engineering. He is Director and Host of the TCF^2HRC and faculty advisor to the Trinity College Robotics Study Team.

IGOR M. VERNER

Igor M. Verner is a Lecturer of Technology Education and a coordinator of teacher-training programs in technology/mechanics at the Department of Education in Technology & Science, Technion, Israel. He received a M.S. degree in Mathematics from the Urals State University (1975) and Ph.D. in computer aided design systems in manufacturing from the Urals Polytechnical Institute (1981), Sverdlovsk, Russia.