Robot Contest as a Laboratory for Experiential Engineering Education

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By designing, building, and operating autonomous robots students learn key engineering subjects and develop systems-thinking, problem-solving, and teamwork skills. Such events as the Trinity College Fire-Fighting Home Robot Contest (TCFFHRC) offer rich opportunities for students to apply their skills by requiring design, and implementation of autonomous robots that are tested during competition. Started in 2003, the TCFFHRC Robotics Olympiad offers junior-high and high school students, working alone or in teams, to demonstrate their knowledge by taking a challenging 50-minute written examination in four key areas related to robotics: mechanics, sensors, software, and electronics. The Olympiad comprises a second evaluation medium that supplements a regular contest survey, which has been in place since 1999. The contest survey solicits information about motivation and progress in subject areas from all contest participants--a large and diverse group that includes junior-high and high school students, working engineers, university students, and team supervisors/guides. As a further evaluation step, we have conducted supplementary case studies of courses and curricula at Trinity College and at the Technion. Assessment indicates that the TCFFHRC has achieved its primary goal: to foster and improve robotics education on an international scale.

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1. INTRODUCTION

Many educators have found that robotics is a suitable subject for project-based learning at undergraduate and high school levels [Martin 2001]. Experience in designing, building, and operating robots leads to the acquisition of knowledge in high-tech engineering areas and promotes development of systems-thinking, problem-solving, and teamwork skills that are in high demand in industry. The involvement of students in a robot contest offers the additional educational benefits of a focused, open-ended, interdisciplinary project that is a strong motivator of student creativity, self-directed learning, and research [Martin 2001].

Educational robotics relies on the concept of *constructionism* [Harel and Papert 1991]. This concept characterizes learning processes in which a learner is involved in the

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creation of external and shareable artifacts. The learner uses artifacts as "objects to think with" in order to explore, embody, and share ideas related to the topic of inquiry. Case studies show that the constructionist approach effectively educates students of all ages and levels of experience and stimulates their intellectual maturity [Kafai and Resnick 1996].

Robot competitions present numerous successful examples of robot systems developed by students. The student teams design and build autonomous robots and program them to perform assignments defined by contest rules, while the scoring is based on robot performance. Recent intensive development of different robot contests motivated a discussion of their methodical aspects and values in engineering education [Murphy 2001; Verner and Waks 2000; Pack et al. 2004; Sklar et al. 2004]. In this debate educators emphasized the value of robot contests as facilitators of team design experiences and interdisciplinary learning, and proposed different models for integrating contest projects in the curriculum.

The goal of this article is to examine the experiential learning processes related to team-based robot design projects among teams and individuals competing in the Trinity College Fire-Fighting Home Robot Contest (TCFFHRC). Robots competing in the TCFFHRC 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, challenging participants to develop generalized maze-solving algorithms. In the Junior, High School, and Senior Divisions, the robots know the maze geometry in advance. The maze for those three divisions includes four rooms and connecting hallways. The candle is placed randomly in one of the rooms and the robot must navigate autonomously to within 30 cm. of the flame before putting it out. The reader will find detailed descriptions of the maze and the rules on the contest site [Trinity College 2005].

2. EARLIER STUDIES AND NEW QUESTIONS ASSESSMENT

Since 1999 we have administered educational surveys at the fire-fighting contests at Trinity. The initial survey objective was to get contestant feedback and general information about the projects. Since 2001 the survey has become part of the contest registration procedure and an instrument for evaluating educational activities and outcomes. The number of respondents equaled 243 in 2001 and 342 in 2002, enabling us to analyze responses of undergraduate engineering students and high school pupils separately as two statistically significant groups.

Parallel to the survey studies, we have conducted case studies of specific fire-fighting programs at Trinity College and at Technion. The case study at Trinity focused on integrating fire-fighting robotics throughout the four years of undergraduate education, and upgrading the contest assignment in the expert and senior divisions [Ahlgren 2001]. The Technion study scrutinized learning through designing, building, and operating robots in the framework of high school graduation projects [Verner and Hershko 2003].

The earlier studies 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. The disparity of evaluations had become an initial point of the new study: we assumed that it might stem from differences in instruction and that optimizing instruction would afford improved outcomes. In this context, our article focuses on the principal didactic problem of project guidance, balancing two goals: (1) to create a working robot prototype capable of performing the contest assignment; and (2) to provide a systematic theoretical framework for understanding engineering subjects. We treat this problem by emphasizing the following three research questions:

(1) Which subjects should teachers address as students design robotics systems?
(2) How can we best integrate learning with the process of producing a robot?
(3) How can the robot contest facilitate learning and assessment of students?

3. EXPERIENTIAL LEARNING CYCLE

The Kolbian cycle model of the experiential learning process [Kolb 1984] is widely cited in engineering education literature. According to this model, experiential learning should be organized as a cyclic process, which consists of four steps:

(1) carrying out a particular action;
(2) perceiving effects of the action through observation and reflection;
(3) understanding the general principle under which the particular instance falls through abstract conceptualization; and
(4) application through action in a new circumstance within the range of generalization.

Kolb pointed out that the four-step learning cycle improves understanding and links theory with practice. Leifer emphasized the need for engineering education to "develop (and assess) special critical thinking skills to map abstracts to hardware and back again," and proposed a product-based learning (PBL) formalism in which the Kolbian learning cycle is embedded in the process of designing a mechatronics system as a way to provide the alliance of the technical and instructional goals of the course [Leifer 1995].

Following this approach, our article presents ways to integrate experiential learning cycles in robot design projects and to evaluate their outcomes. We consider typical experiential learning activities of the fire-fighting robot project, and our new TCFFHRC initiatives, including the TCFFHRC Olympiad, aimed to facilitate learning. The TCFFHRC Robotics Olympiad is a new assessment vehicle that directly tests students' theoretical knowledge in four robotics-related subject areas: mechanics, electronics, programming, and sensors. Following the presentation of the Olympiad, we discuss new assessment results provided by the 2003 contest survey, draw conclusions, and outline new directions.

4. FIRST-YEAR ENGINEERING COURSE

This section describes the Trinity course ENGR 120 (Introduction to Engineering Design), an entry-level offering based on experiential learning through teamwork, experimentation, and design. Created in 2000, the course equips students with basic knowledge of robotics through the semester-long design of a fire-fighting robot. Further, the course encourages students to experience a Kolbian learning cycle by requiring them to expand their basic knowledge by designing, in an open-ended way, robots that will meet a final competition—the class robot Olympics. As reported, ENGR 120 introduces prospective majors to the engineering field and informs them about the discipline and philosophy of design using team-based fire-fighting robot design as the main educational vehicle [Ahlgren 2001]. The desired educational outcomes are (1) development of an awareness of the engineering profession; (2) enhancement of communication skills; and (3) development of basic engineering skills through hands-on robot design. Such engineering skills develop naturally through the semester as students design, integrate, and test their robots. Such skills include teamwork, the ability to use lab instruments, and to develop software programs for sensing and robot control. In ENGR 120, students write their programs using Interactive C [Martin 2001].

In 2003, the 24 students enrolled formed 8 three-student teams with randomly-selected membership. The instructor assigned a mentor, an undergraduate who had completed the course, to serve as the team advisor and facilitator. Each week, the mentor joined the team for a one-hour meeting, during which the team discussed project management, team organization, and team-related interpersonal issues. In addition, the mentor and the team met in a weekly one-hour workshop, led by teaching assistants, which focused on developing technical skills, including programming methods, soldering and construction, and use of instruments. The text served as the primary reference [Martin 2001]. To prepare for fire-fighting robot design, students carried out several projects from the book, including development of Braitenberg vehicles and wall-following algorithms [Braitenberg 1984].

4.1 Experiential Component

Working in a well-equipped robot-engineering laboratory, ENGR 120 teams carry out a sequence of seven workshop projects and experiments that lead to the completion of their fire-fighting robots. Each is described below.

Project 1. *Introduction to programming with Interactive C* (*IC*). Students write IC programs that control Phoenix, a fire-fighting robot that placed first in the 1998 TCFFHRC. The exercise exposes students to dead-reckoning, wall-following, and maze navigation.

Project 2. *Introduction to the Handy board*. Students are introduced to the Handy board [Gleason 2005] and to PC-based cross-software development. They develop and download IC programs that illustrate use of arrays, timers, and elementary motor control.

Project 3. *Design of the Handy bug*. Using Legos and the Handy board, each team builds a wall-banging robot, following the outline presented in Martin [2001, ch. 2]. Teams make oral presentations about their designs and enter their robots in a wall-banging class exhibition.

Project 4. *Braitenberg vehicle design*. Teams develop a robot that follows light sources and responds to collisions with walls. Students construct two light sensors, measure their responses, learn to use the Handy board analog-to-digital ports to acquire data from them. The workshop introduces students to applications of circuit laws (Ohm's law, Kirchhoff's laws) and improves practical skills (soldering, programming, interfacing).

Project 5. *Range sensors* (*two workshops*). Teams test ranging sensors and develop and test wall-following algorithms; this project is described in detail below.

Project 6: *Flame and stripe sensor design* (*two workshops*). Teams add a flame sensor (an infrared photo-transistor mounted in a reflector) and a stripe sensor. The latter detects the white stripes that mark room entrances in the fire-fighting contest maze.

Project 7: *System integration*. Students add a software-controlled fire extinguisher and integrate all hardware elements of the robot.

Project 8: *Navigation*. Teams fine-tune their robot's software and make final preparations for the class contest that qualifies robots to compete in the TCFFHRC.

Creating a successful navigation scheme challenges students, especially by requiring that they integrate knowledge about sensors, computer interfacing, and programming. Successful maze navigation requires reliable sensors; options include IR rangers, small cameras, or ultrasonic devices [Sharp 2005; Acroname 2005]. Project 5 above introduces students to the Sharp GP2D12, which offers a useful range of roughly 10 cm to 50 cm, and so is well suited for navigating in the TCFFHRC maze. The GP2D12 emits a modulated IR beam that reflects off of nearby surfaces. The reflection is focused by a simple lens onto a position-sensitive detector (PSD) that allows distance to be computed via triangulation. This triangulation method is insensitive to changes in reflectance and color. The Sharp sensor has a three-wire analog interface consisting of power (+5 Volts), Ground, and Signal. In Project 5, students build a cable to connect these lines to the Handy board and add a low-pass filter to reduce noise. They write programs to acquire sensor data and carefully measure the sensor's response over the 5-50 cm range. In the second part of this exercise, each team develops and tests a wall-following algorithm that relies on data from the Sharp sensor. The wall-following exercise introduces the concepts of negative feedback and closed loop control; it also introduces timing issues related to the sensor's internal conversion delays.

Experimental measurement of the response versus distance curve of the GP2D12 addresses important learning outcomes:

- knowledge of computer interfacing and analog-to-digital conversion;
- ability to perform computer-based real-time measurements;
- ability to measure, record, and analyze the response curve of the Sharp sensor and to compare results to published data and other teams' measurements; and
- ability to experimentally evaluate the sensor's limitations, including conversion delay issues and errors caused by physical limitations.

For example, students discover that the Sharp sensor readings are not unique: the sensor yields the same output voltage for two distances, one below 10 cm. and one above.

Since many students do not have prior programming experience, a particularly important learning outcome is their development of project-driven programming skills. For many students, the programs developed in Projects 1 to 4 are the first they have written in any programming language. Project 5 builds upon this base and provides students with fundamental knowledge they need to develop full maze navigation codes. In Project 5 students develop and test left and right wall-following codes and develop codes for basic turns. Students learn through experimentation that accuracy of dead-reckoning suffers as motor-supply batteries discharge, so students are encouraged to develop sensor-based turns using multiple GP2D12 sensors. By combining wall-following codes, turning codes, and stripe-detection codes, students develop complete navigation programs.

For example, the program below, developed by Trinity student A. Tamrakar (Trinity '01), causes the robot to search through the fire-fighting maze's four rooms while searching for the flame. When the flame is found and extinguished, the robot returns to the home position. In this code, a function home-to-one causes the robot to (1) navigate from the home spot into room 1; (2) search for the candle; and (3) extinguish the candle if found. If the candle is found in room 1, the home-to-one function returns the value 1; if not, it returns 0. Other functions (two-to-three, three-to-four, two-to-home, etc.) operate in a similar way. Each of these functions relies on lower-level functions that implement wall-following, turning, candle-sensing, and extinguishing. Tamrakar's code, listed below, motivates a discussion of functions in C and demonstrates top-down programming ideas that organize thinking and simplify debugging.

```
void main()
/*  Function home_to_one navigates robot from starting   */
/*  point to room 1 and searches for candle. home_to_one */
/*  returns value of: 1 if candle found and extinguished */
/*                  0 if candle not found in room 1     */
/*  Robot returns to home spot after finding the candle  */
/*  Robot will navigate through maze once               */
{
if (home_to_one()) one_to_home();
```

```
  else if(one_to_two()) two_to_home();
  else if(two_to_three()) three_to_home();
  else if (three_to_four()) four_to_home();
}
```

As described in Section 3 of this article, the experiential Kolbian learning cycle begins with a particular action, whereby students are expected to perceive the effects of the action, to understand the related general principles, and finally to apply the general principles to new circumstances.

The robotics focus in ENGR 120 encourages students to learn under this Kolbian paradigm in many ways; two examples are given below.

The first ENGR 120 workshop illustrates basic concepts of robot operation by requiring students to write programs that control the motion of an existing robot using the robot's sensors. The workshop encourages students to reflect on, inquire about, and subsequently understand fundamental relationships among sensors, electrical signals, interfacing, and computer programs. This generalized understanding, the core of real-time data acquisition and control, is subsequently applied throughout the semester to the design of other robots.

The team's main assignment—in which the team designs, integrates, and tests a fire-fighting robot—serves as a centering experience that encourages the design of robots for the final class competition, the robotics Olympics. The Olympics requires teams, over a two-week period, to generalize and apply knowledge of robot-sensing and control, which was gained through their experiences in designing the fire-fighting robot. Recent Olympics events have included speedy wall-following, line-following, freestyle (2002), cooperative ball-pushing (2003), beercan bowling, robot relay race, and Lego sumo (2004).

In cooperative ball-pushing, two robots, designed by two cooperating teams, must push a 12-cm rubber ball down a long hallway. The robots must not touch the walls or each other. The robots that push the ball the greatest distance win the competition. The cooperative ball-pushing exercise is, within the framework of teamwork, an example of the generalization and application of knowledge to a new problem area, i.e., cooperative robotics. In cooperative robotics, teams apply their knowledge and experience gained through fire-fighting robotics to address new issues related to cooperative robot behaviors and control.

ENGR 120 integrates teamwork, experimentation, measurement, and software development in a theme-based robotics environment. Students acquire basic engineering skills that equip them to move forward to more advanced courses. The course serves as a model for experiential learning in the first year of undergraduate study.

5. ROBOTICS OLYMPIAD

In this section we describe and evaluate the Robotics Olympiad, offered in pilot form as part of the 2003 TCFFHRC, and then in 2004 as a regular component of the contest. To our knowledge this is the first time that a theoretical round has been included as part of a major robot competition.

Olympiads in science and mathematics are popular events that offer students opportunities to demonstrate their knowledge through competitive examinations. Examples include the international Olympiads in mathematics (IMO), physics (IPhO), chemistry (IChO), biology (IBO) and informatics (IOI). The Olympiads official sites and recommended literature are available at [International 2005]. It is worth mentioning that all the Olympiads except IMO offer both theoretical and experimental competition rounds. Others examples include the United States and Australian National Science Olympiads that cover physics, chemistry, and biology. Information about these interdisciplinary events is available at Science [2005] and Australian [2005]. Such Olympiads bring together the best high-school competitors from the around the world and bear considerable weight when comparing educational systems among countries.

5.1 TCFFHRC Olympiad Implementation

The goals of the TCFFHRC Olympiad includes the following:

- to measure student knowledge beyond that indicated by robot performance;
- to promote academic achievement in robotics subjects;
- to provide a bonus to augment robot performance scores;
- to reward the most knowledgeable individuals and teams; and
- to provide an incentive for future Olympiad participation.

The advance announcement of the Olympiad on the 2003 TCFFHRC official site mentions the following points:

- the written test will cover the four areas of mechanics, electronics, software, and ;
- the Olympiad will be for junior and high school competitors;
- for each age group there will be two divisions: one for teams and one for individuals;
- each division will have its own awards and certificates;
- the team and individual tests will be 50 minutes long; and
- if a robot fails to extinguish the candle during the contest trials, then its contest score will be enhanced with bonus points earned in the Olympiad.

Students in both individual and team divisions took the same exam. Participants in the first TCFFHRC Olympiad included 2 individual junior students (grades 6 and 8); 6 individual high-school students and 10 high-school teams with a total of 45 team members.

5.2 Exam Design and Content

The exam consisted of 13 multiple-choice questions covering the 4 subject areas mentioned above. Each of the authors contributed questions to the exam, and the lead author served as the exam editor. Some of our questions were original, other questions explored ideas taken from mechatronics books and aptitude tests. We generated questions across a range of topics and levels of difficulty. Each question presented a real problem that could arise during the robot project and required a solution based on a theoretical background and practical experience in robotics.

5.3 Sample Questions

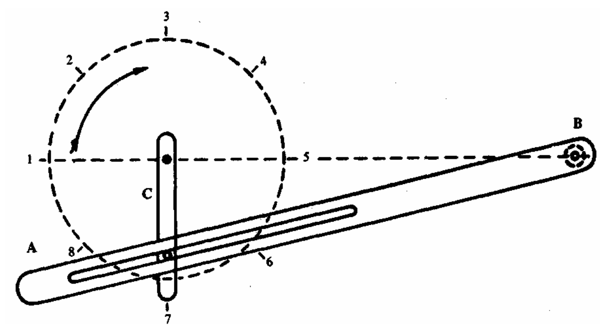
We present four sample questions that appear on the 2003 TCFFHRC Olympiad exam. The four questions cover four subject areas and indicate the level of difficulty, our approach to question development, and student response. The first sample question is straightforward, requiring factual knowledge about battery technology. Students who had engaged in optimizing robot performance when designing their fire-fighting robots would have compared the power-to-weight ratios for different battery types, and so would be prepared to answer this question.

Q1. *What type of battery has the greatest energy density per kilogram of battery mass*?
(a) *Lead-acid* (b) *Lithium* (c) *Mercury* (d) *NiCad* (5) *Carbon-Zinc*

The second sample question tests students on the basic concepts of translational motion and the ability to visualize the dynamics of this mechanism. Basic preparation for this question stems from a background in physics.

Q2. *In the diagram below, crank arm "C" revolves at a constant speed of* 400 *RPM and drives the lever "AB". When lever "AB" is moving the fastest, arm "C" will be in position*

(a) 1
(b) 5
(c) 6
(d) 7
(e) *none of the above* (a) *to* (d)



The third sample question integrates two ideas, i.e., a fundamental programming structure (nested for loops) and robot motion. The variable limit on the inner loop makes this a more challenging question, and requires students to carefully examine each pass through the inner loop.

Q3. *What distance passes a mobile robot after performing the following program*? *A command "Forward K" means move forward K cm*.

(a) 15 *cm*
(b) 35 *cm*
(c) 55 *cm*
(d) 75 *cm*
(e) *none of the above* (a) *to* (d)

```
Integer K, N
For K=1 to 5
    For N=1 to K
        Forward K
```

The fourth sample question integrates three main concepts from the field of energy: storage, conversion, and electromechanical efficiency. The question requires students to understand the concept of battery capacity and to equate stored potential energy in the battery to gain in potential energy as the robot moves to its final position. The question also requires students to estimate the value of the tangent.

Q4. *A robot that weighs* 2.2 *kg is equipped with a* 9.6 *volt battery with a rated storage capacity of* 100 *milliampere-hours. The robot uses two d.c. drive motors. The overall efficiency of the robot, including friction and electrical heating losses, is* 43%. *Starting with a fully charged battery, the robot climbs a* 15-*degree incline at a constant velocity until the battery runs out. Approximately how far will the robot travel along the incline*?

(a) 73 *m* (b) 127 *m* (c) 191 *m* (d) 257 *m* (e) *none of the above* (a) *to* (d)

5.4 Exam Results

We tabulate below the fraction of correct responses for each of the four sample questions and for each of the competition categories (Table I).

Table I. Fraction of Correct Responses by Question and Category

Category	Q1	Q2	Q3	Q4
Individual Junior (N=2)	1	0.5	0.5	0
Individual HS (N=6)	0.5	0.83	0	0.17
Team HS (N=10)	0.9	0.6	0.3	0.2
Overall	0.78	0.67	0.22	0.17

The results in Table I suggest that these Olympiad questions presented a challenge for all participants. It is evident that questions Q1 and Q2 were less of a challenge than Q3 and Q4, which involved the integration of knowledge from different areas. Q4 required the highest level in the integration of knowledge and received the weakest response. The data for Q3 and Q4 is consistent with choosing answers at random. We believe that developing the students' ability to integrate knowledge is an important goal in educational robotics, one that will guide student learning and the development of the Olympiad.

It is also interesting to compare the overall scores across the competition categories. Table II presents the minimum, median, and maximum scores for the categories. Although it is evident that teams performed better on the exam than individuals, the improvement was not marked. In fact, the two junior students performed at nearly the same level as the high school individuals and teams, showing that interest and knowledge in robotics can begin at an early age among highly motivated youngsters.

Table II. Scores by Category (N = 13 Questions)

Category	Min.	Median	Max.
Individual Junior (N=2)	6	7	8
Individual HS (N=6)	3	6	10
Team HS (N=10)	3	7.5	9

The first TCFFHRC Olympiad was successful in engaging junior and high school students in a significant competitive event outside the regular robot competition. The Olympiad, gave students the opportunity to demonstrate knowledge of the theoretical aspects of robotics, complementing the overall skills (both theoretical and practical) that promote success in the robot competition: design skills, hands-on skills, and teamwork, for example.

The 2003 Olympiad test was also given at the 2004 Botball Robotics Competition in San Jose, California. Over 100 students took the exam, including middle school and high school pupils, university students, and graduate engineers; about 80 exams were taken because some people took the exam in groups. An informal postmortem by about 20 test-takers was generally favorable; in future programs the botball event will include theoretical tests.

6. CONTEST LEARNING OUTCOMES: THE 2003 SURVEY

Starting in 1999, the authors have conducted formal evaluations of the TCFFHRC surveys and reported on the results [Verner and Ahlgren 2002]. The survey goals moved from a focus on general information and contestant feedback about their robot projects to the analysis and evaluation of learning experiences and outcomes. The survey's validity has been increased through the following actions:

- increasing the survey's population by making it part of the contest registration procedure;
- comparing the students' self-assessment to the teachers' evaluation data;
- using a subsequent survey to validate results of previous ones; and
- verifying survey findings via case studies of fire-fighting programs at different institutions.

In the 2003 contest survey we sent separate forms to contestants in 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 the 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 (due to the student's participation in robotics studies and in the fire-fighting robot project) and asked the student to estimate his or her progress in each of them. The work-skill development section listed the fire-fighting robot's main subsystems and asked the student to specify his or her contribution to the 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 the average progress of their students in the same disciplines, skills, and abilities as seniors and experts. In the instruction and assessment section, the supervisors described their instruction and assessment methods in guiding the fire-fighting robot project.

The 2003 contest survey forms were completed by 240 participants, including 133 contestants of the school divisions (55.4%); 82 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 in previous surveys.

6.1 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 in Figure 1, which consists of two curves. The curves represent the time scores of the robots that won the first 10 places at the 2002 and 2003 contests in the high school (Figure 1a) and senior divisions (Figure 1b). As indicated by the diagrams, the 2003 scores in both divisions were better (lower) than in 2002; that is, their range narrowed and differences between neighboring places diminished. We consider this an important argument for upgrading the 2004 TCFFHRC assignments.

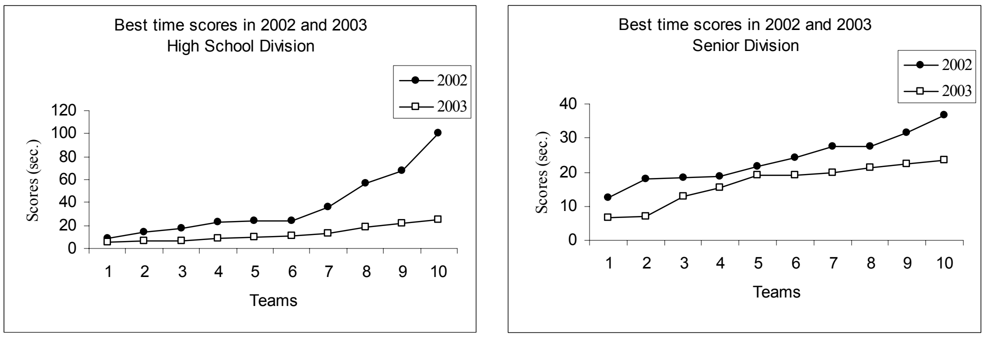


Fig. 1. A comparison of the top 10 robot scores, 2002-2003.

6.2 Curricular vs. Extracurricular Projects

Previous surveys indicate 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. We asked whether the two modes of participation provide equal opportunities for teams to win the contest. This question is especially topical for the high school division, where winning the contest is a more important motivator than for other divisions [Verner and Ahlgren 2002]. To answer our question we compared the achievements of two groups of high school teams in the 2003 contest. Teams in the first group studied robotics in formal courses; teams in the second group via extracurricular activities. Data analysis indicates that achievement in the first group was significantly higher than in the second group ($P_{value}<0.05$). The percentage of robots that successfully passed the qualification round to enter the contest was significantly higher in the first group (85.2%) than in the second group (55.5%).

6.3 Academic Achievement

Previous surveys indicate that university and high school students evaluated their progress in theoretical and practical knowledge in a number of subjects positively, due to participation in the fire-fighting robot projects. In the 2003 survey, as in previous ones, an absolute majority of students reported on 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 student advances in skills and changes in attitude. The kinds of skills and attitudes measured in the survey were similar to those used to assess advances in learning in cooperative education [Parks et al. 2003]. The survey results are summarized in Table III.

The first column in the table includes factors that we divided into three categories: project skills, general skills, and attitudes. The second and third columns present percentage of university students who reported on considerable progress and some

Table III. Students' Advance in Skills, and Attitude Change (%)

Factors	University students		High school students	
	Considerable	Some	Considerable	Some
Project skills				
Ability to work with others to accomplish a goal	54.7	42.2	69.1	26.8
Ability to identify, formulate, and solve problems	50.0	50.0	69.9	29.3
Ability to function on multi-disciplinary teams	48.4	48.4		
Ability to set priorities	48.4	50.0	51.2	39.7
Ability to design and conduct experiments	46.9	48.4	64.2	28.5
Ability to make decisions	46.9	48.4	64.2	28.5
Practical work experience	45.3	48.4	56.1	34.1
Ability to take initiative	43.8	53.1	52.9	42.1
General skills				
Practical application of core knowledge	29.7	64.1		
Leadership skills	26.6	56.3	32.5	49.6
Writing skills	25.0	35.9	19.5	26.0
Oral presentation skills	20.3	48.4	17.9	31.7
Understanding of organizational culture	18.8	46.9	26.0	39.0
Communication with professionals in the field	14.1	42.2	19.5	41.5
Understanding physics	10.9	64.1	35.0	48.8
Ability to apply mathematics	10.9	51.6	38.2	38.2
Attitudes				
Motivation to learn science-technology subjects	42.2	43.8	49.6	43.1
Interest to specialize in science or engineering	46.0	42.9	46.3	43.0
Clarification of career goals and expectations	17.2	62.5	22.8	48.0

progress for each of the factors. The fourth and fifth columns provide similar information about high school students.

The features that become apparent in the table are as follows:

- Almost all university and high school students reported making progress in their project skills due to participation in the fire-fighting robot project; half of the students evaluated their progress as considerable.
- Many students in both divisions reported making progress in general skills, but only 10-30% evaluated the progress as considerable. Some students did not mention having made any progress in general skills.

- The majority of students were positive in evaluating the impact of the robot project on their motivation to learn and interest in specializing in science and engineering; there was less progress in clarifying career goals and expectations.

6.4 Robot-Making

As shown by previous surveys, the majority of university and high school students reported making significant contributions to the design, construction, testing, improvement, and installation of their robots' subsystems. In the 2003 survey we observed differences in the experiences and contributions of the students in the various teams in the high school and senior divisions. We found seven typical areas to which students made contributions, which characterize their experience in the project; the areas are listed in the first column of Table IV. The second and third columns show the percentage of students on the high school and senior division teams who contributed to each of the areas.

Table IV. 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

Table IV indicates that the largest group of students in both divisions (about 40%) contributed to the 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 the 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. The contributions of students from the sixth and seventh groups was limited or not specified. The data in Table IV supports our belief that differences in the students' experience of the project may determine what they learn in fire-fighting robotics, and should be addressed in assessments of learning outcomes. One issue to address is how team organization affects learning and how best to organize teams to achieve the best learning outcomes.

7. CONCLUSIONS

The overarching goals of our work are to improve learning opportunities for students and to carefully evaluate the impact of the contest through regular surveys. We have provided an example of an undergraduate introductory course that uses the fire-fighting contest as the medium for experiential learning of engineering design concepts and the development of the students' technical knowledge and skills. We have also described the TCFFHRC Robotics Olympiad and presented results of the latest TCFFHRC outcomes survey. Current indications are that the 2003 Olympiad was successful and that the Olympiad component should continue to be part of the TCFFHRC program. Also indicated by our survey is the need for increasing the level of challenge in the robot competition, addressed by rules changes starting with 2005 contest.

The Olympiad results indicate that performance levels on the 2003 exam among junior and high school students were remarkably similar, with slightly higher scores by teams. On questions that required integration of knowledge from two or more of the target subject areas (mechanics, software, electronics, sensors) performance was weak in all groups. We recommend therefore that instructors focus on developing integrative skills among their robotics students and regularly challenge them to answer test questions that require application of integrative skills. Teachers also need to balance the time devoted to developing hands-on skills against the development of a strong theoretical framework.

The 2003 outcomes survey indicates, in part, the need to make the contest more challenging, at least for the high school and senior divisions. In response, rule changes were implemented in 2004 and 2005 for the expert division; for example, in 2004 a search and rescue task was added; in 2005 the expert division will admit robot swarms. In addition, for 2005, the other contest divisions were upgraded by changing the arena. The changes include the addition of a staircase, household clutter, and household decorations, including wall décor and mirrors.

The survey also shows that well-organized teams like those that are part of national programs or are associated with formal courses fare significantly better in the contest than do unaffiliated teams or individuals. This finding indicates a possible need for reviewing and perhaps reclassifying the categories in order to promote fairness. Finally, our data shows strong evidence of the contest's general success in promoting robotics education, both at the high school and undergraduate levels. Thus demonstrating that the TCFFHRC has achieved its main educational goals. Through continuing evaluation and assessment, the contest will continue to increase its role in fostering robotics education internationally.

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