Robotics Olympiads: A New Means to Facilitate Conceptualization of Knowledge Acquired in Robot Projects

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Abstract

This paper proposes theoretical robotics competitions, offered in conjunction with robot contests, as the framework to foster deep learning of concepts which underlie the practical projects and to facilitate the development of engineering aptitude. We present our experiences with integrating theoretical tests in the Trinity College Fire-Fighting Home Robot Contest and National Botball Tournament.

Introduction

Robot competitions are recognized as effective motivators, guides, communicators, and evaluators of project-based engineering and CS education [1]. With rapidly increasing level of sophistication and reliability of robots required by the contests, educators are upgrading robotics curricula to provide adequate background knowledge for the new projects. This paper focuses on a key attribute of robotics education, i.e. learning science and engineering concepts which underly practical activities of a robot project. We propose to facilitate understanding by introducing theoretical tests (Robotics Olympiads) as integral parts of robot competitions. We present our experience of theoretical tests at the Trinity College Fire-Fighting Home Robot Contest [2], and Botball Tournaments [3].

Teaching for Understanding and Aptitude Development

Many of the characteristics that we would like the students to acquire in robot projects and demonstrate at the robot contests are implied in the concept of engineering aptitude. Aptitude can be defined as a capacity or potential for achievement in a subject based on the ability to understand phenomena and principles both formally and through experience [4]. The three components of aptitude are knowledge, ability, and motivation. Engineering aptitude characterizes the readiness of the individual to master engineering and technology or to pursue an engineering/technical career [5]. Aptitude tests include engineering and technological problems, which require understanding theoretical concepts and ability to use them in practice [6].

Development of aptitude and understanding is not an automatic result of any learning process. From studies in mathematics and science education, students can acquire knowledge and routine skills without understanding their bases [7]. Unger pointed out [8, 9], that in order to facilitate students' understanding, instructors should be required to: (1) design a curriculum around topics connected to students' interests and experience, and that are central to the discipline; (2) clearly articulate and share with students goals of understanding; (3) engage students in performances that cause students to do a great deal of thinking when using, applying, and enriching their knowledge and skills through challenging work; and (4) practice assessment that actively involves students in reflection on their learning.

Olympiads in science, mathematics, and other subjects [10] are popular events that facilitate teaching for understanding and offer students opportunities to demonstrate knowledge, abilities, and motivation through competitive examinations. Several of them offer both theoretical and experimental components. These Olympiads bring together the best high-school competitors from the around the world and bear considerable weight when inspiring in-depth understanding and aptitude development.

The wide scope of subjects, practical and technical skills that students can gain through robotics education make it an ideal environment for development of their engineering aptitude. In order to inspire this development we have organized theoretical robotics competitions (Robotics Olympiads) in which students demonstrate in-depth understanding of robotics concepts. The conjunction of practical robot contests and theoretical tests provides a framework for comprehensive assessment and reflection needed for effective learning and aptitude development.

Robotics Olympiad Exams

Implementation at Trinity

The first robotics Olympiad was held in 2003 as part of the Trinity College Fire-Fighting Home Robot Contest (TCFFHRC) [11, 12]. The TCFFHRC Olympiad exam aims: (1) to measure student knowledge independent of robot performance; (2) to promote academic achievement in robotics subjects; (3) to provide bonuses that augment robot performance scores; (4) to reward the most knowledgeable individuals and teams; and (5) to provide an incentive for future Olympiad participation.

The TCFFHRC Olympiad exam covers four fields central to designing fire-fighting or Botball robots: mechanics, electronics, software, and sensors. Knowledge of mechanics enables students to develop drive systems and mechanisms and to develop some understanding of robot kinematics. Knowledge of electronics allows students to develop sensor circuitry, understand signals and noise, construct interfaces, and develop signal conditioning circuits. Software design concepts are needed to develop efficient programs for sensing, navigation, and control. Knowledge of sensors and their limitations is key to realizing effective robot navigation and control. In our view robotics is an ideal interdisciplinary medium for teaching for understanding many important engineering concepts related to hardware-to-software interfaces, programmed control of motor drive systems, and issues of energy storage and conservation.

In the Olympiad's first two years (2003 and 2004) the exam was open to registered individuals and teams in the Junior and High School Divisions. In 2005 and 2006 the exam was opened up to all divisions. All Olympiad participants take the same exam, and the tests are 50 minutes long. Each division has its own rewards and certificates, and Olympiad winners automatically qualify for the final performance competition.

Implementation at the NCER/Botball Competition

The National Conference on Educational Robotics (NCER) is held annually. This four-day multi-track conference is formatted like most other mid-sized (about 400 registered attendee) conferences, however about 80% of the registrants and over half the presenters are below the age of 19. The speakers (with the exception of the plenary speakers) are middle and high school educators or Botball team mentors. The conference also contains several special events including the World Botball Championships, the Beyond Botball Tournament, the robot trivia contest, and an adaptation of the TCFFHRC Olympiad. (see www.botball.org for more information). The NCER conference has events scheduled from 8 am until 9 pm each day. The Olympiad, which is open to all registered participants at NCER, is scheduled just before dinner on the second day of the conference. When given the option of having a longer dinner break or taking a written exam (the Olympiad), more than 100 (out of approximately 300) contestants each year take the exam.

The breakdown of the population taking the Olympiad has been very similar for the three years over which the exam has been given at NCER. 10% of the participants are adults. A few of these adults are high school teachers while the rest are Botball mentors who are often professional engineers. The remaining 90% of the Olympiad participants are evenly split between middle school and high school students. About half of the participants choose to enter the Olympiad as teams (interestingly, most of the adults enter as teams; there were slightly more middle school teams than high school teams; there are usually two mixed age teams each year). In 2004 the test used at NCER was based off the 2003 TCFFHRC Olympiad with programming questions added (14 multiple choice questions in total). The test questions were edited slightly based on feedback from earlier users of the test. In 2005, the test was a subset (10 short answer questions) of the 2004 TCFFHRC Olympiad. Again, the questions were edited slightly for clarity, based on feedback. In 2006, the format returned to multiple choice and contained questions based on the 2005 TCFFHRC Olympiad.

Olympiad Exam Design and Content

The Olympiad exams given at the TCFFHRC and the Botball tournament have consisted of ten to thirteen questions across a range of difficulty. Two of the authors contributed questions to the exam, and the lead author was the exam editor. The third author performed additional editing and clarification of the questions. The authors formulated some of the questions themselves, while others were inspired by questions found in mechatronics books and on aptitude tests. Each question presented a real problem that might arise during the robot project, and each required a solution based on theoretical background and practical experience.

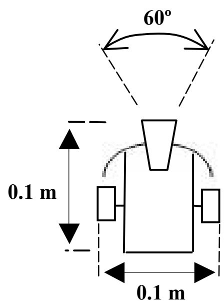
For robotics Olympiads the authors preferred closed and short-answer questions, as distinct from science and mathematics Olympiads which typically offer open questions. The reasons why, for our opinion, closed questions better fit the objectives and limitations of the tests are as follows:

- Within the limited (1-hour) time slot afforded for the Olympiad in the robot contest program we ask 10-15 multiple-choice questions that examine knowledge in different robotics areas.
- Closed questions are suitable for testing heterogeneous knowledge (factual, conceptual, and procedural).
- The contestants sometimes can deduce the correct answers intuitively, using practical experience which is part of their robotics aptitude.
- Closed questions are convenient for collective participation in the test which is preferred by many teams.
- Closed and visual questions suit the contest in which some participants are not native English speakers.

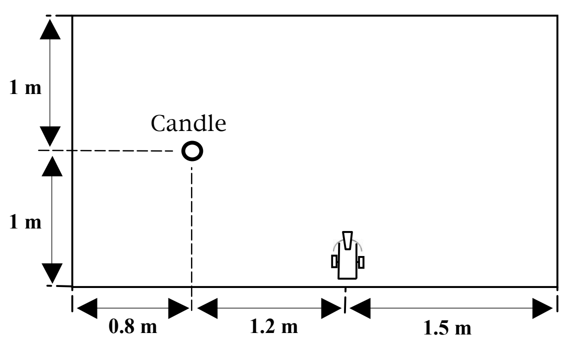
The following sample question, taken from the 2004 TCFFHRC exam, relates to sensor-based robot navigation. Proposed by Joe Jones of iRobot, Inc., the question encourages students to think at the behavioral level when considering the fire-fighting contest task.

Question: A task for the mobile robot shown in (A) below is to find a source of light (a lit candle) in a rectangular room (B) and reach it. The robot employs three behaviors: (1) Escape, initiated after the robot has collided with a wall (Escape causes the robot to draw back 0.1 m from the wall and turn left in a direction parallel to it); (2) Target, initiated when the candle sensor with a viewing angle of 60°, placed on the robot's front, detects light (when light is detected, the robot drives to its source using sensor feedback and stops after reaching the light source); and (3) Forward, in which the robot drives straight forward without any conditions. Escape has the highest priority, Target the second priority, and Forward the lowest priority; the robot chooses Forward when Escape and Target are absent.

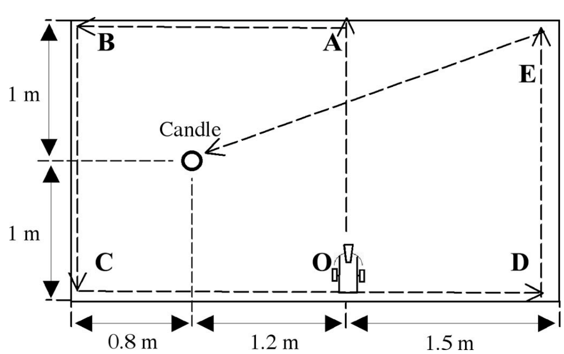
(A)



(B)



(C)



Solution: Refer to (C) above. The robot can't see the candle from the initial position O so it moves upward until it hits the top wall (point A). The robot can't see the candle from any point on this first segment. It enters Escape mode, backs up 0.1 m from the wall, and turns left. From that position (and from any point on A-B), it cannot see the candle, so it moves in Forward mode until it hits the left wall (point B) and enters Escape mode again (moving back 0.1 m and turning left). In a similar way the robot goes to points C, D, and E. From point E the robot sees the candle so it enters Target mode and drives to the candle.

Olympiad Exam Results

Trinity College Fire Fighting Robotics Olympiad

This section briefly discusses results from the 2006 TCFFHRC Olympiad. Table I presents the tasks of the exam questions and the percentage of correct answers to the questions given by high school and university students.

Table I: 2006 Olympiad Questions—Correct Answers (%)

Ques.	Problem Task	HS	Univ.
1	Compute relative speeds of gears in compound gear train	53.8	75.0
2	Determine ratio of output torque to input torque in compound gear train	38.5	25.0
3	Determine projectile speed in compound catapult	46.2	25.0
4	Identify rechargeable battery technology	53.8	87.5
5	Describe robot behavior in a maze given initial position and navigation algorithm	61.5	62.5
6	Determine sensitivity pattern of a reflectance sensor based on sensor element geometry	61.5	87.5
7	Describe behavior of d.c. motor in response to H-bridge input conditions	53.8	62.5
8	Determine how high a 1kg mass can be lifted by draining a certain battery, given system losses	7.7	25.0
9	Analyze response of series circuit containing a resistor and a light-emitting diode	0	25.0
10	For differential drive robot of known geometry, determine turning radius for given wheel velocities	0	25.0
	AVERAGE SCORE %	37.7	50.0

The data suggest that the Olympiad questions presented a challenge for both high school and university participants. Questions Q4 and Q6 received the greatest number of correct answers. Correct solution to Q4 requires factual knowledge about battery technology, a subject that many students have considered in their robot design. Q6 required use of trigonometry to determine the overlapping region of sensitivity of an IR emitter and a phototransistor. The strong response of high school students to Q6—even stronger than the response of university students—might imply that the high school students have studied and applied trigonometry more recently.

The correct responses to Questions Q1, Q5, and Q7 were in the 50-65% range so these problems appeared to be more challenging than Q4 and Q6. High school students had a higher percentage of correct responses on Q1 than did university students, but high school and university students had similar levels of success with Q5 and Q7. It is clear that high school students held their own even in this second level of difficulty (=unclear=). Questions Q2 and Q3 were even more challenging, yielding average responses in the 30-47% range. High school students did better than university students on these latter two questions.

Questions 8-10 received the smallest number of correct answers. Among high school students there was only one correct answer to Q8 and no correct answers to Q9 or Q10. Q8 required test-takers to apply basic definitions of stored electrical energy, gravitational potential energy, and conversion efficiency to compute the height to which a certain mass can be raised by a specified charged battery. Q8 requires integration of knowledge from physics and mathematics and its solution requires application of energy conservation principles (physics of gravity, efficiency, energy conversion). The next question, Q9, required estimation of the current in a series circuit containing a light-emitting diode, with known voltage/current curve, and a fixed resistance. Q9 required students to set up circuit equations and to find an sufficiently accurate solution to a non-linear equation describing the current. Q10 posed a fundamental problem in differential drive system, to determine the radius of curvature of motion when the wheels are turned at given speeds. This last question required students to apply facts about the robot's geometry including wheel diameter and separation geometrically to derive an equation for the radius of curvature. These last three questions required a more advanced level of analytical skill than the other questions. Even the university students achieved only 25% success rate on these questions.

Table II presents the minimum, median, and maximum scores for across the competition categories.

Table II. Scores (correct answers) by Category

Category	Min.	Median	Max.
Team University (N=8)	3	5	8
Team HS (N=11)	1	3	5
Individual HS (N=1)	7	7	7
Individual Junior (N=1)	4	4	4

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, evidence that interest and knowledge in robotics might begin at an early age among highly motivated youngsters. We also conclude that high school teams were not inferior to university teams in mechanics and programming and that generally the university teams were better in electronics and sensors.

The TCFFHRC Olympiad was successful in engaging junior and high school students in a significant competitive event outside the regular robot competition. Through the Olympiad, students were given the opportunity to demonstrate knowledge of 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.

NCER Olympiad

The National Conference of Educational Robotics Olympiad scoring has been done slightly differently. When the test is multiple-choice, the questions are graded as 5 points if answered correctly, 0 if left blank, and as -1 in the event that an incorrect answer is given – to reduce random guessing. The Olympiad results from the NCERs are interesting in several respects. Teams from a particular age group scored on average slightly above the average of the individual scores for that age group. However, with the exception of the adults in 2004, no team obtained the high score for their age group during the three years of test data. In 2004, the high scoring adult group (a group of senior engineers from a major defense contractor) tied the score of the high scoring individual high school student. The highest scoring middle school student was always lower than the highest scoring high school student. In 2005 the top high school score beat the top adult score. In 2006 it was the other way around. Results for the 2006 NCER test are shown in Tables III and IV.

Table III. Scores by Category (15 Questions)

Category	Min. Score	Median Score	Average Score	Average %	Max. Score
Individual Junior (N=18)	-7	10	9.0	13.8	32
Team Junior (N=3)	11	11	11.7	18.0	13
Individual HS (N=13)	-1	22	25.1	38.3	54
Team HS (N=8)	14	24	24.1	37.1	38
Individual Adult (N=4)	15	41	39.0	60.0	59
Team Adult (N=4)	29	33	35.5	54.6	47

The average team size for the 2006 NCER Olympiad was slightly over 4 people, there were 35 individuals taking the test and approximately 60 people as 15 teams taking the test. Each year, the percentage of test takers taking the test as teams has risen despite the teams never really dominating the winners. Note that there was not necessarily much correlation between the makeup of the Botball competition teams and the Olympiad teams.

Questions such as the example question Q4 above are normally not covered in public schools until high school physics (a class that is usually taken during the junior or senior year, if it is taken at all). However, a small but significant number of middle school students correctly answered questions such as Q4 and other questions dealing with digital circuits that are normally not covered anywhere in the public school curriculum. It is not clear how students were able to correctly answer these questions (especially on the 2005 test where they had to write out explicit answers).

The college/adult category scored an average of 60%, the high school category 38%, and the middle school category 14%. On average, individuals performed better than teams in the college/adult category, equal to teams in the high school category, and worse than teams in the junior category. This is somewhat surprising since team skills are something that is actively taught in high school and college engineering programs, yet team skills/benefits on the Olympiad seem to deteriorate with age. It is possible that those forming teams as adults are doing so because they are less confident in their Olympiad skills than those taking the test individually, while at the junior high level the student teams are based more on social groupings than assumed skill level.

Table IV. Correct answers to the Olympiad questions (%)

Problem subject	Univ. & adults		High School		Middle School	
	Individ.	Team	Individ.	Team	Individ.	Team
1. Degrees of freedom	50	75.0	30.8	25.0	16.7	0
2. Torque	100	100	84.6	87.5	72.2	100
3. Gear train	75	100	92.3	87.5	38.9	50.0
4. Stepper motor	100	100	84.6	100	66.7	75.0
5. Electric circuit	75	50	76.9	62.5	50.0	50.0
6. Energy	25	0	0	0	0	0
7. Power consumption	75	25.0	46.2	37.5	16.7	25.0
8. Batteries	50	75.0	38.5	37.5	11.1	50.0
9. A/D and D/A conversion	50	25.0	23.1	37.5	0	0
10. Robot programming	75	100	53.8	50.0	16.7	50.0
11. Sensors	100	50	23.1	25.0	0	75.0
12. Step climbing mechanics	50	75.0	38.5	12.5	0	0
13. Sensors	0	0	7.7	25.0	11.1	0

Q1, degrees of freedom question, had much better responses as age of test taker increased. The notion of degrees of freedom is likely not introduced at the middle school level, introduced in some high schools, and certainly introduced in university courses. Q2, Q8, Q10, Q11 gave reasonably close responses from all groups. Q9, Q12 likely covered topics that are not introduced early on. Junior and high school participants suffered on these questions. Q6, Energy question, challenged all test takers. This question focused on conversion of stored electrical energy in a battery to increase the gravitational potential energy of a mass with given system efficiency. The poor response to this question among all test takers indicates a gap in their physics backgrounds. We consider this an important area that deserves greater emphasis in courses and projects.

Participants of the 2006 NCER Olympiad expressed their opinion about the exam in the survey which asked to evaluate to what extent the exam questions correspond to given characteristics. The survey results are summarized in Table V.

The first column of the table includes the survey question and the list of seven characteristics. The next columns present for each of the characteristics percentage of the participants who consider it relevant or completely relevant to the exam. All the participants found the exam difficult and challenging. For our opinion, the questions were not too sophisticated, but as follows from the table, they were unfamiliar to the majority of students. The students agreed that the questions are appropriate for robotics studies and examined theoretical understanding, but pointed to their limited practice of theoretical problem solving and low attention to theoretical considerations in their robot projects. Many students' reflections on the exam, added to their survey answers, indicated that our goal to raise the awareness about the need of theoretical problem solving in robotics was achieved.

Table V. Relevance of the Olympiad exam characteristics

To what extent the Olympiad Exam questions were:	Univ. & adults		High School		Middle School	
	Individ	Team	Individ	Team	Individ	Team
Challenging	50	100	100	100	100	100
Difficult	100	100	100	100	100	100
Unfamiliar from past experience	0	85	75	88	69	100
Appropriate for robotics studies	100	75	89	75	75	100
Connected to your robot project	50	0	11	13	25	100
Examined theoretical understanding	50	100	88	75	53	50
Examined practical experience	50	25	38	13	57	50

Conclusion

We have described theoretical robotics competitions (Olympiads), coordinated with two international robot contests, that provide a framework for learning and development of engineering aptitude. Our motivation in Olympiad development is the belief that developing student understanding of engineering concepts and ability to apply and integrate knowledge is an important goal in educational robotics. Challenging questions can provide guidance to improving learning and instruction in robot projects. We have presented a sample problem that illustrated our emphasis on teaching new concepts of robot motion. To answer that problem, students must understand the rules of robot behavior and apply them given a constraint, the sensitivity angle of a flame sensor. This problem suggests that teachers need to stress the importance of careful reading, understanding problems, and synthesis of knowledge when developing a solution. We note that Olympiad problems that require integration of knowledge are especially difficult for the test taker. Since teaching for understanding necessarily presents to students problems that require integration of knowledge, we encourage teachers to focus on making challenging assignments that require students to integrate knowledge as an everyday exercise.

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