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Using Robot Competitions to Promote Intellectual Development

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■ This article discusses five years of experience using three international mobile robot competitions as the foundation for educational projects in undergraduate and graduate computer science courses. The three competitions—(1) AAAI Mobile Robot, (2) AUVS Unmanned Ground Robotics, and (3) IJCAI RoboCup—were used in different years for an introductory undergraduate robotics course, an advanced graduate robotics course, and an undergraduate practicum course. Based on these experiences, a strategy is presented for incorporating competitions into courses in such a way as to foster intellectual maturation as well as learn lessons in organizing courses and fielding teams. The article also provides a classification of the major robot competitions and discusses the relative merits of each for educational projects, including the expected course level of computer science students, equipment needed, and costs.

Design competitions are becoming increasingly common, especially in the field of mobile robots. The sponsorship of such competitions ranges from local clubs of enthusiasts to large professional organizations, such as the American Association for Artificial Intelligence (AAAI), which sponsors the annual AAAI Mobile Robot Competition and Exhibition as part of its annual conference. Awards for competitions vary from certificates of merit to significant prize money, such as the Association for Unmanned Ground Vehicle Systems (AUVS) Annual Ground Robotics Competition awards of $5000 to its first-place winner, $3000 to the second place, and $2000 to the third.

The Colorado School of Mines (CSM) has been a leader in fostering the intellectual development of its students through design activities (Pavelich and Moore 1996). One outcome of this emphasis has been the incorporation of national design competitions directly into the classwork of the Introduction to Robotics and Computer Vision (junior-senior level), Advanced Robotics and Computer Vision (graduate level), and Field Session (computer science design practicum) courses offered by the Department of Mathematical and Computer Sciences. The intent of these efforts is to improve students' design competence and intellectual maturity by taking advantage of the opportunities afforded by robot competitions.

This article reviews experiences associated with these courses and their design teams over a five-year period. The design teams met the objectives of each course, earned 1 first-place and 4 third-place awards plus $5000 in prizes, and produced 7 papers. Based on these positive experiences, I encourage others to integrate competitions into classes and offer recommendations on how to facilitate the process. Although the focus of this article is specific to classroom education, it is expected that these observations will also provide insight into the incorporation of design competitions into the general educational experience. A competition can reinforce key concepts of a course and bring reality to an AI robotics project as well as produce a viable entry. Other teaching opportunities not covered in class, such as budgeting and improving communication skills, are not discussed in this article.

The article begins by contrasting the objectives of competitions and educational experiences. The conclusion is that certain portions of competitions can be an important tool for fostering intellectual maturity, as defined by the Perry model (Pavelich and Moore 1996). Next, a classification of the major international robot competitions is presented. Background information on the courses is presented and how this information influenced the matching of classes to a specific competition. How the courses were organized to take advantage of the competition topics is discussed next, with particular emphasis on grading and class size, the spectrum of philosophies for managing competitions, and the difficulties with cooperative learning. A section on fielding a team by integrating the class projects is also included. The article concludes with a synthesis of the experiences at CSM into a general strategy for incorporating a competition into a robotics course.

Competition versus Education

Competitions focus on winning (although some define winning in terms of design rather than performance), whereas education concentrates on teaching the methods that ultimately lead to success.

The goals of a competition often have a surface intersection with the topics addressed by education. However, competitions focus on winning (although some define *winning* in terms of design rather than performance), whereas education concentrates on teaching the methods that ultimately lead to success. Instructors use a variety of techniques in the classroom, most notably laboratory exercises and projects, to ensure that each student has the opportunity to meet the learning objectives. The Perry model suggests that a competition can aid the intellectual maturity of students who are beginning to accept that there might be more than one correct answer to a problem. The primary issue for an instructor is how to identify and integrate the appropriate aspects of a competition into the laboratory and project assignments.

Competition Goals

The sponsors of robot competitions generally cite the following reasons for the competition: to evaluate progress of the community in some aspect of mobile robotics, for example, walking platforms; to encourage undergraduate students to get more experience with mobile robotics, thereby improving both the quality of students going into the work force and the number of students willing to make a career in robotics; to expose undergraduate students to faculty and research issues, thereby encouraging them to consider graduate school; to encourage graduate students and their advisers to consider pressing but unsolved issues facing robotics; and to have fun. In effect, they are mini–grand challenges of a field to encourage interdisciplinary interactions between academic researchers in the hopes that such endeavors will become commonplace.

The potential impact of these competitions on research should not be underestimated. The AAAI national conference hosts increasing numbers of demonstrations of software agents playing competitive games.

Competitions and the Perry Model

Although competitions clearly offer something to the research community, they also offer a more immediate payoff to the general educational development of the individual student. A competition provides additional extrinsic motivation for the students to mature, according to the Perry model of intellectual development (Culver, Woods, and Fitch 1990).

Perry's model defines nine stages of increasing complex reasoning: Positions 1 and 2, *dualism,* reflect a student's attitude that right and wrong answers exist for all problems. At position 3, *early multiplicity,* students realize that knowledge includes methods for solving problems and that there can be more than one right answer to a problem. Students reach position 4, *late multiplicity,* when they begin to think and analyze about the diversity of possible solutions. At position 5, *relativism,* students evaluate solutions from different contexts. At positions 6 through 9, *commitment within relativism,* the students are able to take into account that the world is a changing place.

A competition involves a clearly defined—but open-ended—problem to which there are many possible solutions. The students must be largely self-reliant to understand the problem and apply their knowledge and problem-solving methods; they must function at the least at the early multiplicity position. Working voluntarily with other students encourages the student to identify and evaluate a variety of opinions stemming from the scientific literature, the professors, and other students, which should move the student to a late-multiplicity position. The typical team organization of an adviser plus student members lends itself to a realization of relativism, whereby the teacher serves as a consultant instead of an arbiter. The goals of the competition, as opposed to other potential applications of robotics, serve to stress the contextual aspect of applying knowledge.

In addition to the general intellectual maturation of the student, a competition provides a forum in which to acquire and exercise specific job-related skills. Mobile robot competitions, in particular, require sophisticated software, interdisciplinary interactions, and teamwork. It is difficult for the students to make progress without applying good software-engineering principles, especially testing and debugging strategies. The students will probably need to collaborate with students from other disciplines; for example, the smooth control of a mobile robot depends both on the power train and on how fast the software can update what the next move should be. A good competition is designed so that it is virtually impossible for a one-person team to succeed; so, interpersonal and project management skills are continually challenged within the team and refined.

Issues in Using Competitions

Given that a competition offers an opportunity for intellectual growth, the real guidelines in capitalizing on the educational opportunity include the following:

Identify where the students are on the Perry model scale and what aspects of the competition will help them to reach the next stage. Each class is different, but a useful heuristic is to assume that the majority of the undergraduates are at position 3 (early multiplicity). Internal assessments of graduating seniors at the Colorado School of Mines indicate that the majority have not reached position 4 (late multiplicity) by graduation. To reach students at positions 3 and 4, the instructors should identify topics within the competition and focus on how the methods covered in class apply to solving these topics rather than on how they generate novel solutions. One approach is for the instructor to specify a small set of approaches taken by previous entrants to one aspect of the competition (for example, topological navigation), have the group of students read the associated papers, and present an evaluation of why these methods succeeded (or not). A position 4 group, for example, gifted undergraduates, might be given a more-open topic and only one or two starting places in the literature.

Ensure that the appropriate educational component is integrated into the competition experience. A competition offers the potential for an educational experience, but it doesn't guarantee it. As with other team projects, negative events can reinforce a student's tendency to shun teamwork ("I could have done it better by myself.") or transfer responsibility to another agent ("It was my partner's/the hardware's/the software's/the competition sponsor's fault"). The competition experience should be orchestrated so that the students have a reasonable chance to succeed if they proceed correctly, discern the cause of failures as they occur, and make correction if possible to prevent such situations from occurring in future projects. The relatively low level of intellectual maturity of undergraduates favors the instructor providing the overall architecture and design so that the students work on portions that are both relevant to the course and have a high potential for being completed.

Shelter students from extraneous concerns. Competitions often involve many activities that would not be encountered in a typical laboratory experience: acquiring-maintaining hardware, raising money, and so on. Although these activities are likely to be part of a student's future career, they can take valuable time and attention away from the objectives of the course. Learning how to do a budget cannot replace learning how to program with reactive behaviors in an introduction to AI robotics course or replace the reinforcement from applying techniques covered in class to a real-world project.

These guidelines maximize the learning experience in terms of advancing intellectual maturity. However, the professor will have to spend additional time restructuring a competition into "class-sized" pieces as well as supporting all the remaining responsibilities. This restructuring can be too much for professors attempting to balance research, service, and other classes with some semblance of a personal life. Therefore, the following item is added to the list of issues:

Minimize the burden on the faculty adviser. In addition to the effort required to integrate the competition into a class project(s) and supervise progress, the competition is likely to necessitate extracurricular activity and travel, which places additional demands on the faculty member as well as ties up various research resources (laboratories, workstations, robot platforms) and travel money. Therefore, the faculty adviser must have a strategy for both incorporating the competition into the classroom and managing extracurricular demands.

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A Classification of Competitions

The ROBOHOO web site (www.robohoo.com) has a list of major competitions and links to their home pages. *Robotics and Autonomous Systems* publishes synopses of recent and upcoming events in their Robotics Competition Corner section.

Robot soccer is currently very popular, both in its RoboCup and MIROSOT (also known as FIRA) forms. These competitions emphasize facets of multiagent control, although MIROSOT tends to be less about AI and more about building microrobots. The Association for Unmanned Vehicle Systems (AUVS) sponsors three competitions: (1) ground, (2) aerial, and (3) underwater (a new addition). These competitions tend to pose grand challenges that persist for four or five years until the state

Competition	Expertise: Hardware	Expertise: Software	Educational Level: K	U	M	P	Support New Teams?	Equipment Restriction ?
AAAI[1]	W	S	N	W	S	S	Y	N
AUVS[2] Aerial	S	M	W	W	M	S	N	Y
BEAM[3]	S	N	S	S	N	N	Y	N
AUVS[2] Ground Robotics	S	W	N	M	S	W	N	Y
Khepera	N	S	W	W	S	S	Y	Y
MIROSOT	S	M	W	M	S	S	Y	Y
RoboCup	M	S	W	W	S	S	Y	Y
AUVS[2] Underwater	S	W	N	N	S	S	N	Y
SAE[4] Walking	S	N	N	S	M	W	Y	Y

1. AAAI = American Association for Artificial Intelligence.
2. AUVS = Association for Unmanned Vehicle Systems.
3. BEAM = Biology, electronics, aesthetics, mechanics.
4. SAE = Society of Automotive Engineers.

Table 1. Rating of the Characteristics of Major Competitions as Strong (S), Medium (M), Weak (W), or Not at All (N) Applicable.

Expertise is either on hardware (H) or software (S); the target participants are either K through 12 (K), undergraduates (U), Master's candidates (M), or Ph.D. candidates (P). Does the event explicitly facilitate new teams (Y/N), and does the event require specific equipment (Y/N)?

of the art catches up. The AAAI competitions vary from year to year, but the events stress software-oriented entries. A new series of events and competitions involving the Khepera robot have gained in popularity. The Society of Automotive Engineers (SAE) Walking Machine Decathlon and the American Society of Civil Engineers (ASCE) Lunar Construction competitions usually generate clever mechanical solutions, ignoring software despite the clear need. BEAM (biology, electronics, aesthetics, mechanics) robotics and its cousin, the International Fire-Fighting Home Robot Contest, are often too simple to reinforce anything beyond the most straightforward reflexive behaviors implemented in circuits.

The various competition web sites often do not give a clear picture of what the competition entails. Murphy (1999) identifies five key questions and attempts to describe the spectrum of answers.

Table 1 shows a subjective rating of each of the major competitions. These ratings are based on an examination of the rules and actual participation for the past years of the competition.

Typical Participants

Possibly the first question an instructor should ask is, "Is the focus of the competition appropriate for the team's intellectual level and goals?" For undergraduate computer science majors, one must ask, "Is the competition suited for computer science majors who tend to be comfortable with programming but not constructing platforms, or does it require significant mechanical or electrical engineering skills? The AUVS Unmanned Ground Robotics Competition poses a vehicle-guidance problem that sounds perfect for AI and computer vision. In practice, the majority of entries are from mechanical engineering departments. Although the course work can emphasize the software portion, a computer science team might not be able to field a viable entry. Some competitions implicitly favor Ph.D. students who are using the competition as a problem domain for a research question (for example, using aerial vehicles as a test case for real-time visual control), but others target providing K through 12 students with an opportunity to work with circuits.

The Expertise and Educational Level columns in table 1 rate the major competitions in terms of the real target participant. The expertise is divided into hardware and software and rated as either weak (W), medium (M), or strong (S). The education level of the team members is divided into K through 12 (K), undergraduate (U), Master's (M), and Ph.D. (P) participants. The participation for each competition is hard to categorize crisply and is treated more as a fuzzy set. For example, successful AAAI competition teams almost always consist of Ph.D. and Master's students, with one or two undergraduate members. Undergraduate teams have tended to fare unevenly. Two high school teams have appeared at the competition, only to quickly withdraw.

A related question is, "How much faculty involvement is necessary?" The answer, of course, depends somewhat on the team, but some competitions are harder than others. In the AUVS aerial competition, the winners tend to be teams led by one or two graduate students whose Ph.D. thesis was a key element. The AAAI competition typically has a clear graduate student flavor; the only undergraduate teams that do well (both in score and in general respect from the robotics community) have had a clear involvement from an adviser active in research. Among the soccer competitions, RoboCup has a strong research focus that suggests a high level of faculty supervision would be needed to field an undergraduate team.

Novice Entries

An important criterion for an instructor to consider is whether the competition is amenable to new teams. Making a competition accessible is a difficult part of being an organizer. The AUVS competitions assume that the team has been working on the entry for years; indeed, the latest aerial vehicle competition is so complex, it expects a three-year commitment. One of the biggest challenges for the AAAI competition is ensuring the events are challenging enough to promote interesting solutions but not so hard that the robots look incompetent to the larger AI community. A new approach in AAAI is to offer an entry-level event focused on the state of the practice. Competitions such as RoboCup explicitly encourage sharing code and hardware designs. MIROSOT offers extensive workshops in the summer for new competitors. Table 1 has a New column indicating whether the competition is generally supportive of new teams.

Equipment Restrictions

Does the competition specify, restrict, or expect certain types of hardware? Clearly, a Khepera competition requires Khepera entries. Other competitions do not specify the hardware, but the rules implicitly favor a certain type. For example, the rules of the AUVS Ground Robotics Competition were originally written with a golf cart in mind as the typical vehicle. Smaller vehicles based on a children's battery-powered jeep were able to take advantage of favorable obstacle layouts. Likewise, recent winners of the AUVS Aerial Vehicle Competition have all been hobby helicopters using differential general problem solving for control. Table 1 has a column entitled Equipment Restrictions that shows competitions that have significant hardware requirements.

The wrong equipment can put a competition out of reach for a team, in spite of the quality of the software. However, the right equipment can be beyond the reach of anyone except researchers active in a particular field, which also introduces the risk of using expensive research equipment for educational purposes. Competitions such as RoboCup and MIROSOT have small leagues where individual robots can be constructed for approximately US$500. MIROSOT goes even further and permits a hardware-oriented team to build vehicles for a software-oriented team. Also, from time to time, robot manufacturers offer to loan vehicles or sensors to certain teams.

Regardless of the source, hardware must be available and reliable for the class to proceed smoothly. Given the demands of research and a general the lack of funding for the replacement of expensive equipment, the use of research equipment for education presents a fundamental conflict. Students new to the area need time on the robot, and faculty and research assistants also require access to the equipment. Classroom students can jeopardize the research activity of a laboratory if they mistreat equipment. The dual use of equipment can literally bring research to a halt. I must note, however, that only minor damage has occurred in the research laboratory during educational use. The students have generally been protective of the robots and felt privileged to be trusted with them.

Time management of robotics equipment for both research and education can be complicated. Student competitions can require that the robot be unavailable for a sizable portion of time. For example, a robot was shipped to RoboCup in Japan. The robot entered the country with few problems and only a day late. (In another competition, a competitor's entry arrived not only late but also upside down, damaging the robot beyond on-site repair.) On return, a rubber wolf mask on the stereo camera pair, to make the robot look more animal like, was not explicitly listed on the manifest. It resulted in more than a two-month delay before the robot arrived back in the United States, significantly interfering with another research project. Contention for equipment also hampers evaluation. Rarely was a class able to access the CSM robots long enough to produce a statistically significant analysis of the robot's behavior. Because evaluation is critical in science, this lack of access is especially disturbing.

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Costs and Rewards

Finally, what's in it for the team? Using a competition for a classroom exercise is one thing, but it is another set of issues to actually enter the competition. Entering a competition means traveling to it as well as shipping the robots. Some competitions offer travel scholarships (although it appears only AAAI maintained this practice for 1999); others offer prizes. To maximize the amount of travel money for students traveling, as well eliminate the week or two associated with shipping, a robot was shipped only once to a competition. Typically, the students and adviser drive to the competition, often spending between 18 and 36 hours together in a van. The first year's travel from Denver, Colorado, to Washington, D.C., was in an non–air conditioned van. The van got so hot, the circuit boards on the robot got soft and flexible to the touch. After that, the team had an air conditioned van! Travel costs for the eight teams discussed in this article averaged $2200 for the robot and four students attending a competition in the United States and $4000 for an international event, including customs fees.

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The rewards to the team also vary by competition and individual preferences. Many students are eager to compete to travel. Others are motivated by prize money. In 1997, a group of advanced students were given the choice of working on three different competitions: (1) AUVS Ground Robotics held outside Detroit, Michigan, offering a $5,000 purse; (2) AAAI in Rhode Island, which was considered the most desirable competition because CSM had a positive history of participation; (3) and a new competition, RoboCup, held in Japan. Funds were guaranteed for travel to Detroit or Rhode Island but not Japan. The majority of the students chose the AUVS competition; the next most popular was AAAI, and one took a chance that funding would become available for a trip to Japan. Ultimately, participation in all three accommodated all students' tastes.

Matching Courses to Competitions

Three different courses resulted in eight teams for three different competitions over a five-year period (1993–1997). Two of the three courses are taught annually during the spring semester: Introduction to Robotics and Computer Vision and Advanced Robotics and Computer Vision. A third course is a follow-up to Introduction to Robotics and is taught for six weeks immediately following the spring semester. The AAAI Mobile Robot Competition and Exhibition and RoboCup World Cup were matched with the Introduction to Robotics course and the AUVS Ground Robotics Competition to the Advanced Robotics course. This section describes each of the courses, justifies the match to a competition, and reports the results. It also provides a discussion of what lessons were learned in matching and how they might transfer to larger classes. The next section details the incorporation of the competition into the course organization.

Introduction to Robotics

Introduction to Robotics is an upper-level computer science course that attracts approximately 15 to 30 undergraduates. The undergraduates are usually juniors or seniors in computer science or engineering. The course is a survey, concentrating on software issues. AI was not a prerequisite, although C++ programming experience and a course in software engineering were. Engineering students typically met these prerequisites by virtue of being enrolled in the computer science elective program. The objectives were the same each year:

> At the end of this course, the student should be able to demonstrate a knowledge of the basic AI paradigms in robotics, the ability to design and implement a reactive behavior, familiarity with common techniques for navigation, competence with common industrial vision and machine-perception techniques, and the ability to integrate sensing and action.

Undergraduate students at CSM are required to take a six-week practicum called Field Session during the summer after their junior year. Students who have taken Introduction to Robotics were eligible to work with permission in the CSM Mobile Robotics–Machine Perception (MR–MP) Laboratory for their field session. Generally the best performers in Introduction to Robotics opt to do so, and for the purposes of this article, Field Session is treated as an extension of Introduction to Robotics. This was the equivalent of offering a special topics or senior design course for the best students the following semester. Introduction to Robotics has been taught five times. Each time, motivating examples and class projects were taken from the AAAI Annual Mobile Competition and Exhibition, and the students attended the competitions. In 1997, when there were 32 students, a group of undergraduate students who had already done robotics laboratory work were permitted to work on a RoboCup entry as their project. In all cases, I served as both the class instructor and the team sponsor.

The AAAI competition was a good match for the introductory course on the conceptual level because the events generally involve both behaviors and navigation, allowing the students to use a hybrid deliberative-reactive architecture. Events typically concentrate on having a robot act as delivery person, going from one room to another, which is routine enough to look easy but challenging in practice. Furthermore, it emphasized software development and integration of existing research ideas as well as putting research into practice. Finally, I have an active research program in similar domains, providing the students with an architecture and reusable code rather than having to write a complex system from scratch.

The competition was also a good match from the hardware perspective because it tended to favor indoor research robots that are either slow and bulky (for example, DENNINGS) or small and mostly harmless (for example, PIONEERS). Either extreme is attractive when teaching undergraduates who might not correctly program the acceleration and velocity gains. Speed is generally not an issue, and the competition arena is similar to a robotics laboratory. The team used a DENNING-BRANCH MRV4 named CLEMENTINE, shown in figure 1a, for four years until she was replaced with CRISBOT, a Nomadic 200, shown in figure 1b.

The primary disadvantage of the AAAI Mobile Robot Competition and Exhibition was that in most years, the specifics of the rules were not posted until the middle of the spring semester. Another disadvantage was that the competition often favored teams that were able to purchase or engineer hardware. For example, in 1995, our team tied with the first-place winner on computer vision performance but took fifth because of a penalty for not having a manipulator on CLEMENTINE.

The 1993 and 1994 teams did not place in the competition because of hardware failures. The 1995 team placed fifth in the Recycling Trash event and was the only team composed solely of undergraduates. In 1996, the Introduction to Robotics team placed sixth in the Office Navigation event. From 1993 to 1996, the teams used CLEMENTINE.

In 1997, the Introduction to Robotics team competed in two events because the larger class size necessitated more project topics. The 1997 team placed third in Technical Challenge and third overall in the Hors d'oeuvres, Anyone? event using CRISBOT. The team earned a third place technical challenge award in the Find Life on Mars event before a frame-grabber failure prevented it from competing in the final round. The robot, SILVER BULLET, was built by an interdisciplinary undergraduate team sponsored by the National Science Foundation through the Research Experiences for Undergraduates Program (figure 1c).

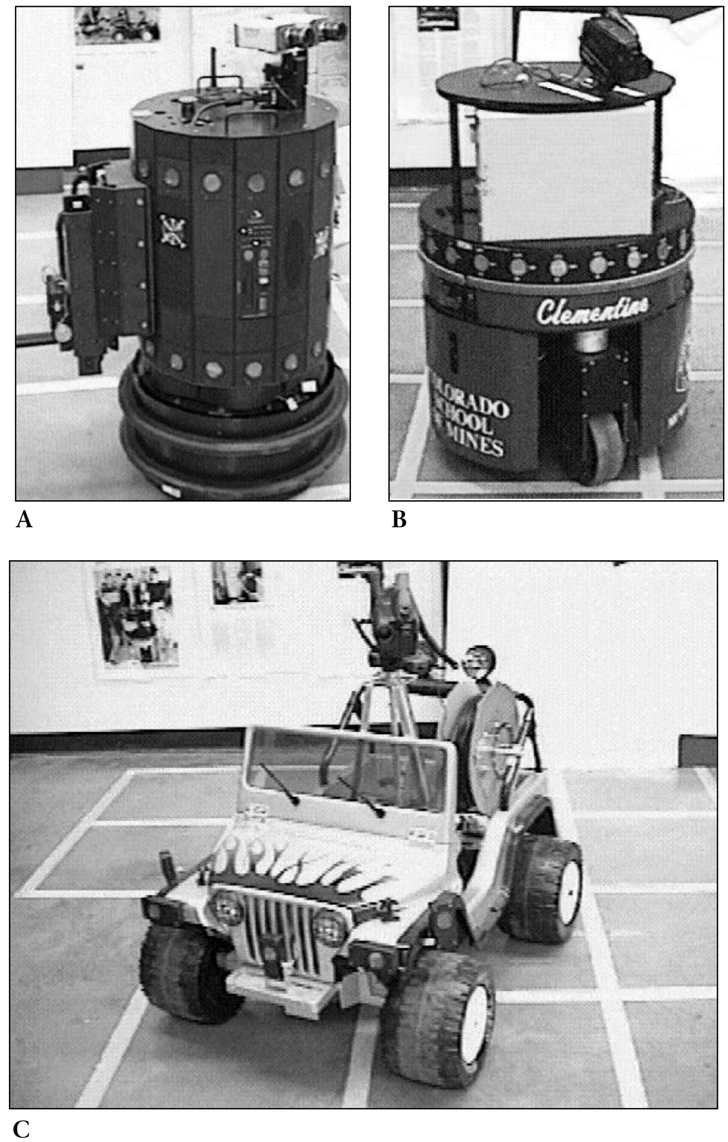

Figure 1. Robots Used by the Introduction to Robotics Course.

A. CLEMENTINE, a Denning-Branch MRV4. B. CRISBOT, a Nomadic 200. C. SILVER BULLET, a custom platform.

The Introduction to Robotics team also participated in the expert demonstration league of the RoboCup World Cup Competition, held in conjunction with the 1997 International Joint Conferences on Artificial Intelligence. Originally, the team was to compete in a large-size league of Nomadic 200 bases, but the other teams did not materialize. The RoboCup entry was able to reuse computer vision routines for segmenting and tracking a ball, allowing the students to concentrate on docking and apply results of evidential reasoning research.

A

B

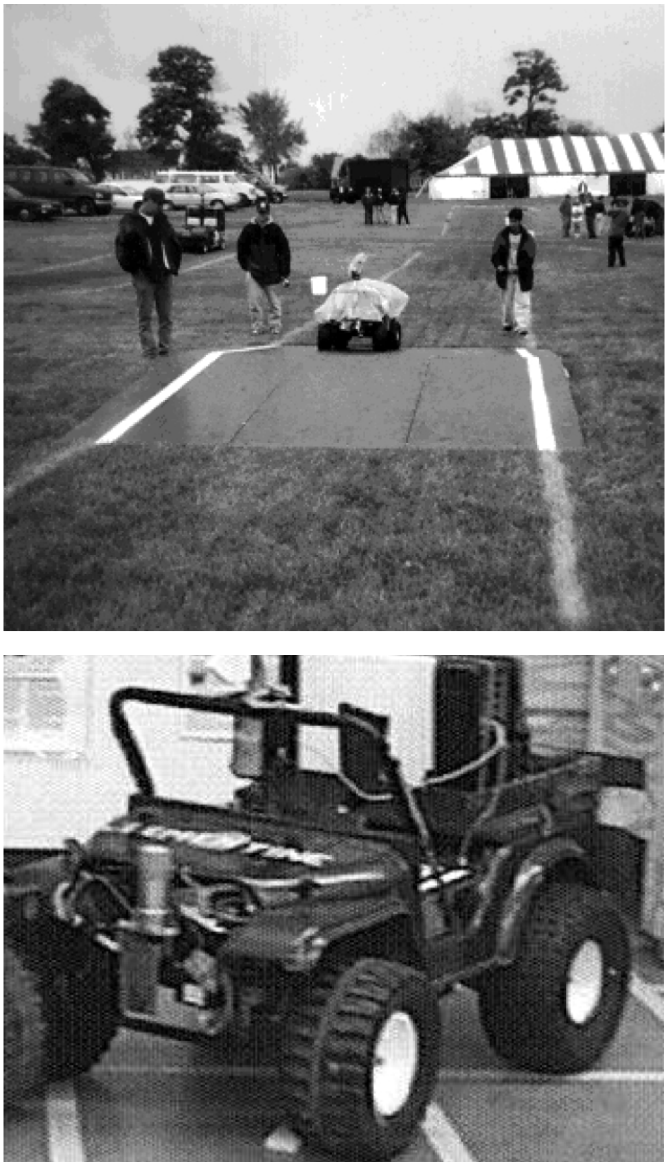

Figure 2. C2 *Robot Used by the Advanced Robotics Course.*

A. On the field during the 1997 Unmanned Ground Robotics Competition. B. A Close-Up View.

Advanced Robotics

Advanced Robotics is a graduate course with five to eight students, mostly from computer science. Half of the students are undergraduates who are taking the course as a technical elective. The course is an advanced treatment of material presented in Introduction to Robotics, concentrating more on AI techniques used in mobile robotics and situated agency.

Advanced Robotics used the AUVS Unmanned Ground Robotics Competition as motivation. The students in Advanced Robotics were better suited to taking care of an outdoor platform (they literally were more likely to bring it in out of the snow and rain) and developing software for a more challenging environment. Advanced Robotics could have used the AAAI competition as well, but because both the Introduction and Advanced Robotics are always taught in the same semester, there would have been significant contention for the robot, and the undergraduates might have been stifled by the graduate students.

The objective of the Unmanned Ground Robotics Competition is to have a robot follow a road (white lines painted on a golf course), avoid obstacles, climb ramps, and so on. Because the competition is outdoors, a standard indoor research robot platform cannot be used, the computer vision component is much more difficult, and testing is more involved. The MR-MP lab was loaned an outdoor robot by Omnitech Robotics, Inc., a local Colorado firm.

In 1995, the team was given the robot outright. Figure 2 shows the robot, C2, at the 1997 competition.

The competition was a good match conceptually but a poor match in practice. The competition participants were largely drawn from mechanical engineering departments. Design documentation was later required by the competition, but the design phase was sponsored and judged by the Society of Automotive Engineers and did not consider software. In addition, the competition was held outdoors, and in 1997, a frame grabber was damaged because of rain. The graduate courses at the University of South Florida (where I have recently moved) do not make use of the Unmanned Ground Robotics competition, given the focus on hardware, the lack of participation by teams from schools with a strong AI program, risk to hardware, and no incentive for innovative AI and computer vision.

The 1994 Unmanned Ground Robotics team took first place and a $5000 prize, and the 1995 and 1997 teams placed fourth and eighth, respectively. All teams are considered successful, but the 1995 team was the most notable. This team used a more sophisticated approach based on a thorough evaluation of the major approaches to vehicle guidance and produced two papers and a software library for use in further research endeavors in vehicle guidance. The 1997 team was plagued by hardware failures. Rain fell almost continuously for the three days of the competition, and the frame grabber shorted out because of moisture. The team did produce an interesting application of visual attention.

Course Organization

The Introduction to Robotics and Advanced Robotics courses were similar in organization, with the competition serving as a theme for the course. Experiences with assigning multiple groups the same subtask were mixed; it appeared to hurt performance in the introduction course but produce good results in the advanced course. Both courses were managed with a coach style of faculty interaction, which assumed that the students were at a position 3 or 4 level of maturity. This coaching style was a balance between the instructor micromanaging the project and true cooperative learning. A true cooperative learning approach was deemed to have serious drawbacks, especially given the intellectual level of the students.

Grading Scheme

The Introduction to Robotics and Advanced Robotics courses used their associated competitions as a theme in all aspects. First, the competition served to motivate classroom discussions of how a particular technique would be applied to a real-world problem. Second, the competition supplied the domain for homework assignments, for example, program a potential field to represent the *X* behavior. If the specifics of the competition for the class were not available, the event of the previous year's competition served as the sources for motivating examples and assignments. In addition, the students used the classroom discussions and assignments as scaffolding for their final project on an assigned topic relevant to the competition.

Grading for Introduction to Robotics was based on four components: (1) 6 to 10 homework assignments (30 percent), 3 tests (20 percent), outside readings (10 percent), and a group project (40 percent). The individual homework assignments often involved programming. They were intended to ensure that each student had tackled each of the major topics of the course, including potential fields, sequencing behaviors, topological and metric path planning, and computer vision. The group project was typically subdivided into equally weighted milestones: simulation of the reactive behavior, implementation of behavior with ultrasonic perception, incorporation of deliberation, replacement of ultrasonic perception with computer vision, and final report. The instructor posted the list of the topics for the project and let the groups decide which one they wanted to tackle.

Grading for the Advanced Robotics course was based on a group project (60 percent) and presentations based on outside readings selected by the instructor (40 percent). The project was also subdivided into milestones: literature search and evaluation, implementation, and final report.

Class Size and Competing Groups

A large number of class members makes it more difficult to ensure that each student participates. In the Introduction to Robotics classes, the competition task was divided into independent subtasks and assigned to each student or group of students as a project. These groups are intentionally small and consist of two to three students. If possible, engineering students were paired with computer science students to promote interdisciplinary interactions. In two of the five years, the Introduction to Robotics classes had many more students than subtasks. In these instances, more than one group was given the same subtask, and the results of each group were compared. As expected, different groups did produce some diversity in approaches and results, but the duplicate assignments also appeared to disenfranchise some groups. Felling less critical to the overall project allowed them to be more indifferent to it: If their code didn't work well, some other group's code would. One solution is to use multiple events or competitions for the project.

Duplicating subtasks among groups produced different results with the Advanced Robotics course. It was common in that course to have groups implement a different method on the same platform and then compare results. This approach worked well because the students were curious to see which technique would work the best. Although the groups were competitive, loudly rooting for their algorithm to outperform the other groups during trials, the groups worked together to fix control problems, develop common code segments, and so on.

The possible negative impact of competition in the classroom is described in Johnson, Johnson, and Smith (1991) and should certainly be avoided. However, in both courses, students were divided into groups only to implement or evaluate cutting-edge research results, not to rank their individual performances. A group is evaluated on its understanding of the approach, the quality of the implementation, and follow-up analysis of the performance. As a result, all groups usually receive an A, regardless of which technique shows superior performance. Competing groups learned as much as if they had all been working together. This observation is consistent with the study by Sherman (1989) on competition versus

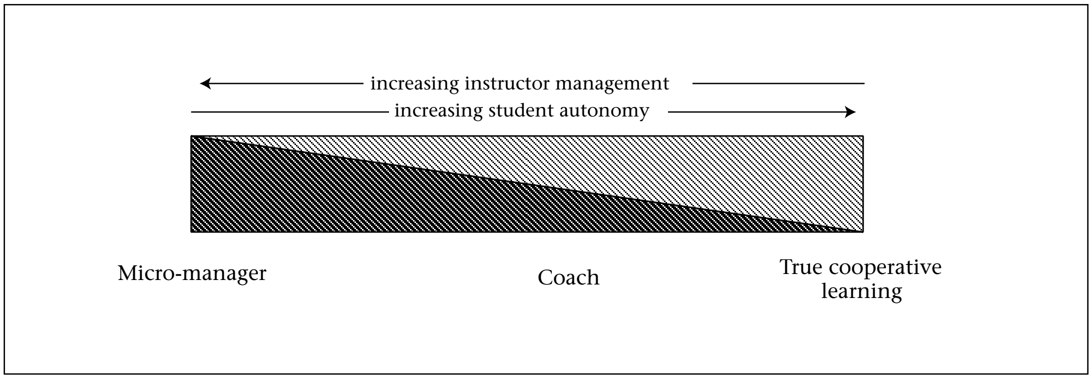

Figure 3. Spectrum of Styles of Managing Competitions.

cooperation when teaching biology.

As an experiment in motivation, a bonus of a half letter grade was awarded to the group in the 1995 Advanced Robotics class that showed the highest performance in each of two demonstrations. In the first demonstration, the student groups had similar techniques, and the bonus grade served only to motivate the students to keep adjusting thresholds on the algorithm during the two-hour–long demonstration. In the second demonstration, one technique was clearly superior to the other, and the bonus grade served no purpose. It did not appear to demoralize the second team because it knew that the difference between an A and an A+ was negligible. The bonus grade was deemed to be superfluous and was discontinued in future classes.

Cooperative Learning Spectrum

In addition to organizing the project to accommodate class size, the classroom instructor needs to consider how to best manage the learning experience. My experience and discussions with other advisers suggest that there is a wide range of styles for managing projects related to competitions, as shown in figure 3. There is the *true cooperative learning* philosophy (Johnson, Johnson, and Smith 1991) that emphasizes student involvement and interaction and little to no instructor involvement. The cooperative learning approach is not recommended, despite its popularity among educators for reasons stated later. At the other end of the spectrum, there is the *micromanager approach*, where the adviser structures every aspect of the experience. This technique was not used for any of the teams because its educational merit and use of time were questionable. Most teams were managed from somewhere in the middle of the spectrum with good results. The middle of the spectrum is the *coach style*, where the instructor closely supervises the activities of the team (intended to encourage intellectual development) and intercedes to make adjustments as needed.

Difficulties with Cooperative Learning

In the cooperative learning approach, the adviser serves as a consultant, or benign remote manager, and the students are expected to self-organize, identify the problems, generate potential solutions, and evaluate the results. This expected level of interaction is essentially at position 5, relativism, of the Perry model. However, undergraduate students are often at position 3 or 4, introducing a severe mismatch between expectations and ability.

The cooperative learning model was used with two teams (1993 and 1994 Introduction to Robotics) with uneven results. The students simply did not have the technical knowledge and methodology necessary to identify problems and good solutions until the end of the semester. Even during the follow-up practicum course, after they had been exposed to the theory, they still did not have enough hands-on experience to effectively apply this knowledge. Formal cooperative learning methods did not seem to enhance the educational process. The students were immediately experiencing the benefits of cooperative learning: engaging in the material, acting as peers with other students and professionals, and developing and refining problem-solving skills. Major obstacles to cooperative learning included a lack of practice and self-confidence in applying their skills. In general, they had not yet internalized the procedure of identifying a problem, generating many solutions, determining evaluation criteria, and applying these criteria to the solutions.

In spite of the mismatch between management styles and the students' level of intellectual maturity, the 1993 Introduction to Robotics team produced a solid entry (although the entry did not place because of a hardware failure) primarily because its task was simpler. The winning team from the Jet Propulsion Laboratory/California Institute of Technology consisted of one person who programmed the robot the night before. The 1994 team was never able to grasp the increased complexity of that year's competition, and both the learning experience and the entry were weak. In contrast, the 1995 to 1997 teams operated satisfactorily under a more structured strategy. These classes were given an overall design for the competition entry and tasked to work on modules that were educationally relevant to the class. Experience indicates that students are best motivated when they can see the "big picture" at the beginning of the semester before they actually begin work. Unfortunately, students are generally not knowledgeable enough to design such a framework at the beginning of a course. More structure, combined with improved hardware, contributed to four third-place awards.

Experience also suggests that the cooperative learning tenet of getting local experts involved is impractical and inappropriate. In one variation of the cooperative learning approach reported by Tribus (1993), students were expected to contact professionals in the field and solicit opinions about what was important, in addition to the other activities. This more extreme cooperative learning paradigm, having the students interact with professionals to research the aims of the course and its projects, is not necessarily appropriate. Mobile robotics is a new field, and the competitions use scenarios that require significant innovation. There are few experts in the field, and the team adviser is likely to be the most knowledgeable person. In addition, the relationship between the university and local industry can be strained by having students constantly query an industrial expert. However, a robot competition sponsored by a national professional society could be interpreted as being cooperative learning because the competition allows professionals and students to interact (although in a more controlled fashion).

Cooperative learning's most important down side is group dynamics. If allowed to work autonomously, both the undergraduate and graduate students tended to generate only one solution to a problem and then "fall in love" with it. The 1994 AAAI team generated a provably more computationally complex algorithm to searching a graph that represented a topological map, ignoring the well-known single-source shortest-path algorithm developed 20 years ago for this specific class of problems. Because this algorithm was one of several software components, the degradation in performance might not have been noticeable. The approach of trial and error, where the students would ideally try their approach and see it fail compared to others, did not seem applicable. Because students were clearly violating a fundamental principle of computer science in applying a less optimal solution, the adviser and practicum instructor each spent two hours attempting to review complexity analysis and algorithm design with the team in an attempt to get the students to change their minds. In the end, the team had to be ordered to use the better algorithm.

Based on these experiences, perhaps competitions are too challenging for the students to function cooperatively at the relativism level and higher without significant support from the instructor. This is particularly noteworthy because it appears that many advisers of undergraduate teams treat them as if the members were at position 5.

This assumes that the students have had sufficient coursework and have a high level of intellectual maturity.

Other instructors are genuinely concerned that they will stifle their students' creativity. In the worst case, this assumption results in a "sink or swim" attitude.

Providing an overarching architectural framework, software modules to work on, and the set of methods to evaluate did not appear to interfere with student creativity. Creative students found (or made) opportunities to infuse the project with their ideas, especially in the follow-up course. By tailoring the class to positions 3 and 4, weaker students consistently did well and often included their project as portfolio materials for interviews.

Integration of Projects

In the Introduction to Robotics courses, integration of the class projects was deferred until the follow-up practicum course. Integration of software modules and software with hardware is essential to producing an entry in a competition, but it involves a great deal of work unrelated to the class. It can be deferred until after the class has been completed. If the instructor's framework is reasonable, and the students have addressed the critical intellectual issues during the class, the smaller set of volunteers or members of an independent study course should be able to readily integrate the modules. Furthermore, because integration is extracurricular, members of the class who were not high performers or were not committed to the team will drop out, and the team will be more productive.

Another advantage of deferring integration is that the instructor can tailor management

Experience also suggests that the cooperative learning tenet of getting local experts involved is impractical and inappropriate.

styles. During class, the instructor acts more like a coach, setting up practice drills, calling the plays, and so on. Based on interactions with the students during the semester, the instructor can decide how much autonomy the follow-up group is able to handle.

The major disadvantage of deferring integration is that gratification is also deferred. Some students might not be able to participate on the team beyond their contributions in class, even if they are high performers.

Recent Modifications

The equivalent to Introduction to Robotics has been taught once at the University of South Florida with an enrollment of 40 students, almost all computer science majors. Because of the larger class size and initial laboratory limitations, no competition was integrated into the classroom. Two modifications are being added to the course to compensate for the larger class size and to reintroduce competitions into the course.

The first modification is the incorporation of Khepera robots as dedicated educational robots, and second, the use of a soccer competition is tentatively planned. Dedicated hardware for the course reduces the problems associated with using research robots for education. Two Khepera robots have successfully been used during a USF Introduction to Robotics project during the last six weeks of the course. Kheperas are relatively inexpensive (US$2000 for a basic model to US$8500 for one with color vision and a gripper) and reliable. An excellent UNIX-based simulator is available (a WINDOWS version is under development) that allows the students to test their code before physically interacting with the robot and possibly damaging it. Their small size (smaller than a soda can) makes it easy to physically set up and create test domains. Initially, the class was allowed to program the robots individually using the simulator. Preliminary knock-out rounds were held on the simulator, and semifinals and finals were conducted on the physical robots during class time. In the future, groups of two or three students will program a team of soccer robots using a MIROSOT or RoboCup small-league arrangement. Another option is to use Tucker Balch's TEAMBOT JAVA simulator, which can be customized for use with any robot platform.

Although the use of a simulator helps manage the contention for hardware resources in a large class, it has the negative consequence of eliminating true hands-on experience. Therefore, the second modification will be to regain exposure to hardware. Lego Mindstorms and Rug Warrior kits will be used in laboratory exercises during the first six weeks of class in place of assignments. These inexpensive kits are well suited for illustrating reactive behaviors and simple perception, and the Kheperas support a project with advanced navigation and computer vision. It is anticipated that many students will purchase their own kit to keep, further reducing the cost of the laboratory to the department.

Fielding the Entry

This article argues that a high degree of structure is useful for integrating the intellectual challenges of the robot competition into a course. As a result, a significant portion of the work needed to field the entry must be done outside class or in a follow-up class or summer Research Experience for Undergraduate format. In the case of Introduction to Robotics, the instructor invited high performers to work on the competition as part of their practicum course. At USF, an independent study course is offered.

Competition activities can provide an additional opportunity for intellectual development. For example, students can now consider hardware. Hopefully, they will have acquired enough intellectual maturity to identify the real issues to generate and evaluate multiple solutions, even if the solutions have little to do with the class material. This section describes issues associated with fostering intellectual development during the extracurricular activities.

The biggest observed impediment to additional intellectual development during extracurricular activities has been group dynamics. The group norms are partially established during class, but student attrition allows the norms to be malleable. Two aspects of the class organization influence the final group dynamic: (1) overall structure of the course and (2) milestones. In addition, having students work on the team in subsequent years is also an advantage. Traditional group performance modifiers, such as writing mission statements, have produced mixed results.

The structure of the projects during class gives the students an implicit standard operating procedure on how the adviser expects decisions to be made outside class: identify problems, generate solutions, and evaluate. Milestones are essentially deadlines.

The dynamics of groups in the class were influenced by project deadlines. These deadlines put pressure on the students and caused the groups to "form" and "storm," using Tuckerman's terms (Gray and Starke 1988). This early state of group development presents a problem at the end of class, when a small fraction of the students in the class elect to work on the team, either for course credit or as a volunteer.

The students who stay are often from different project groups, leaving the roles and norms within the team unclear. Milestones developed jointly with the sponsor and the team serve to put pressure on the team to perform and began evolving toward a favorable dynamic. It can be difficult to arrange responsibilities so that everyone is equally involved. For example, if a student is in charge of hardware, but the hardware does not break during the competition, the student does not feel as if he/she contributed. A possible solution is assigning each student a primary and a secondary area of responsibility. Therefore, a student in charge of hardware would be knowledgeable enough to help test and modify navigation code unless a hardware matter arose.

Continuity in the teams between years is helpful on many levels. A senior can lecture a junior on the importance of software engineering, and the junior learns to have faith in the instructor. The instructor is reassured that the senior actually learned something.

An unexpected positive outcome of two classes using the same robot platform because of hardware problems has been that the undergraduates in Introduction to Robotics have had a chance to mingle with the graduate students in Advanced Robotics. The graduate students provide role models and peer reinforcement. In five cases, the graduate students spontaneously "adopted" an undergraduate student and encouraged him/her to go on to graduate school (three did). Mentoring undergraduates has now become a tradition among graduate students, and the undergraduates are frequently referred to as "virtual grad students." In addition, one talented but unruly undergraduate was reportedly told by a graduate student that his attitude toward the robot was unacceptable, and his behavior subsequently improved without further intercession.

Despite their popularity in business, mission statements written by the teams either during class or during the extracurricular portion have rarely had any effect on group dynamics. Undergraduates at CSM have been exposed to mission statements but largely reject them as a creation designed for the instructor. Graduate students tend to be more amenable to writing mission statements, but they still tend to duplicate the mission of their adviser. Writing a mission statement appeared to aid the positive group formation of only one team. What did seem to work was for the instructor to have a strong mission statement that included student roles and to continually remind the students of this fact. The author's mission has always been to derive the most educational value from the competition. Winning is never part of the mission as such, but students are reminded that because they have addressed the competition with intellectual rigor, winning is anticipated.

An important aspect of fielding an entry is the follow-up. Students will be reluctant to compose an analysis of what happened and why. If the competition is an extracurricular activity, students cannot be forced to submit a write-up. The value of the follow-up report comes from encouraging students to think in analytic terms. The instructor generally knows what happened and why and how to avoid the problems encountered later. Also, the instructor is the one most likely to do the bulk of the writing for any publication.

Fentiman and Demel (1995) present a formal methodology for having students document their design projects and present results. Many of the documents and steps involved would be useful if the sole objective were the competition. The methodology appears significantly time consuming, so much so that it is unclear whether students would complete it voluntarily. An alternative strategy is to request each student produce a one-page report. Because the follow-up report is an important educational tool, it is worth the additional time to repeatedly urge students to submit it. Even if the report is never written down, it will stimulate reflection on the student's role in the project.

Mentoring undergraduates has now become a tradition among graduate students, and the undergraduates are frequently referred to as "virtual grad students."

Conclusions

In conclusion, design competitions can effectively be integrated into coursework. The Introduction to Robotics course consistently earned a much higher rating by the students than the departmental average for courses. At the same time, the course received only a slightly above-average rating on work load, indicating that the project was perceived by the students to be within their capabilities. The Advanced Robotics course received higher ratings than the department average, and one year it was given a 4. 0 rating for the course overall.

A design competition can provide both motivating examples of how abstract concepts can be transferred to practice and meaningful assignments and projects. The added stimulus of the competition encourages the students to put forth their best effort in identifying problems, generating and evaluating solutions, working in a group, and applying knowledge. A competition provides an opportunity to further the intellectual development of a student, particularly because the traditional team organization favors students at the relativism stage of Perry's model. Undergraduate students are unlikely to be at that stage, and the adviser should help the students move toward relativism. Follow-on courses or extracurricular experiences can lead to a competitive entry, as seen by the five awards and seven publications garnered by the CSM teams. Experiences at CSM were gained through small-sized classes but should not serve as a deterrent from trying the described methods.

Many advisers approach teams with a sink or swim attitude, assuming that the students have had enough coursework and experience to succeed on their own or learn from their failures. This assumption places students at the relativism position already. Observations of five undergraduate and graduate classes and eight competition teams suggest that it is better to expect the students to operate at the early multiplicity stage. Rather than expecting students to be autonomous, a more appropriate strategy is to treat the intellectual challenges inherent in the competition as opportunities to practice problem-solving skills and internalize these skills under favorable conditions. As the students reinforce their skills under supervision, they should move toward a position of relativism.

Incorporating a design competition into course work requires a significant investment of time and thought. The instructor must plan well in advance to identify the most suitable competition and adapt the relevant aspects to the class population. The importance of access to hardware and its timely maintenance cannot be overemphasized. Assignments and projects need to be done on a robot to expose students to a realistic experience. If there is a hardware breakdown, learning is disrupted, and the students become frustrated.

Integrating the opportunities afforded by a design competition into a classroom situation should be highly structured. The instructor must identify the aspects of the competition that apply directly to the educational objectives of the class and defer the other aspects to extracurricular activities. The instructor must formulate the relevant challenges of the competition into class projects that are implemented and evaluated. An overarching framework or system architecture must be provided to facilitate students' ability to visualize the overall challenge. Limitations on modifications to the hardware or other systems must also be explicit to maintain student focus on solutions that support the educational objectives. Following the competition and outside class, follow-up reports should be encouraged.

This strategy provides some certainty that the competition itself did not distract from the educational enterprise and that each student should experience intellectual growth. The burden on the adviser is reduced in the long run because the strategy minimizes the frustrations owed to mismatched competitions, erroneous expectations of student intellectual maturity, and lack of focus on the course material. Indeed, the strategy does more than facilitate the integration of a competition into a robotics course.

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