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Designing Contests for Teaching Electrical Engineering Design*

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This paper discusses important issues connected with mounting a junior-year design contest including safety, students' knowledge, students' judgment, creativity, incorporation of course material, design difficulty, strategic and tactical richness, infrastructure and support costs, time required for contest management, and requirements for a successful tournament. The paper concludes with a short discussion of some previous contests with respect to usefulness as a learning tool.

INTRODUCTION

MOST ELECTRICAL engineering programs have a capstone design course in their senior year to provide students with the opportunity to use knowledge gained throughout the program, to gain further insight into the design process, and to improve their engineering judgment. In the freshman and sophomore years, most programs provide very basic engineering design experience through simple design projects and design questions in conventional assignments. The freshman design experiences are largely unrelated to electrical engineering because students do not have the technical sophistication to undertake an electrical design or even the skills required to successfully operate measurement equipment. Thus, the capstone course is frequently the electrical engineering student's only significant, discipline-specific design experience. Students are 'tossed in at the deep end', frequently without knowledge of formalized design methodologies, design management, decision support tools or time management.

At DalTech, we have instituted a significant junior-year design experience in which all students, working in pairs, attempt to solve the same design challenge. This permits students to learn from other groups, to gain (limited) teamwork experience, to have a real measure of their design performance through comparison with other groups, and to gain experience with design methodologies, decision support, time management, group dynamics, engineering trade-offs, etc. prior to the capstone course.

To perform well in the workplace, an electrical engineer requires:

1. factual knowledge;
2. knowledge of engineering procedures;
3. the ability to determine the fundamental concepts operating in open-ended problems;
4. the ability to acquire new, relevant, factual and procedural knowledge;
5. judgment, to make decisions with incomplete and/or contradictory information.

While the normal engineering curriculum addresses items 1 and 2 through didactic learning, items 3, 4 and 5 are developed largely through experience gained on-the-job during co-op workterms, internships or after graduation. This is largely because electrical engineering faculties have chosen to devote comparatively little time to allowing students to develop these skills through open-ended design projects. The confluent pressures of an ever-broadening field and a more academically-inclined faculty have tended to squeeze out those program components which provide design experience. These pressures, coupled with the inherent difficulty of assessing design skills, has resulted in items 3, 4 and 5 being left to others to impart to the students.

DESIGN EXPERIENCE IN CURRENT PROGRAMS

Most programs provide exposure to design at the freshman and senior years. Freshman-year experience is frequently some form of mechanical or structural design such as design of a truss made of balsa wood or popsicle sticks. This exposure is appropriate for all engineering students given their level of engineering education, but does not provide any discipline-specific design exposure for electrical students.

Recent texts provide some level of design exposure to sophomore students through carefully-posed problems. This exposure is appropriate for these students as they have an understanding of the principles of mathematics, physics and chemistry,

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but lack abstraction skills and most technical skills. Sophomore design problems are generally based on extensive analysis, are not open-ended, and are quite straightforward.

Some form of capstone design experience is included in nearly all programs. Design projects are either initiated by faculty [2, 3, 5, 7, 8] or by industry [6]. Student groups of two or three ensure that all students benefit from the experience [7]. Both faculty-initiated and industry-initiated design projects are typically open-ended, complex, and incompletely specified. They usually require students to gain procedural and factual knowledge not provided in class and require the students to exercise engineering judgment. These projects are often typical of the tasks that new graduates will undertake in industry.

There are very few, if any, design experiences offered in the junior year.

Continuity of design experience

Without junior-year design experience, students are asked to 'jump' from closed-ended, well-circumscribed design tasks in the sophomore year straight into open-ended, poorly-defined projects in the senior year, with the added problem of having nearly a two-year hiatus in design. This results in the following problems:

1. Students are tremendously insecure, feeling that they have been 'tossed in at the deep end' in the senior-year capstone course because their design experience does not include simpler, open-ended design projects.
2. Students have very limited opportunities to develop concept-identification skills, knowledge-acquisition skills and judgment because they are exposed to open-ended design only at the senior level.
3. Industry-initiated capstone courses offer little opportunity for students to compare their design methodologies with those of others working on similar problems.
4. Capstone project evaluation is frequently inconsistent because design projects are not usually assessed by a common panel of assessors. This is particularly true of industry-initiated projects.
5. The validity of teamwork experience in capstone courses has been questioned because groups are composed of peers [1].
6. Capstone courses make disproportionate demands on students' time [6]. This is largely a time management and priority-setting issue.

Nearly all of these problems can be addressed by mounting a well-designed junior-year design experience.

DESIGNING THE JUNIOR DESIGN EXPERIENCE

A good junior-year design experience must be based on an open-ended, under-specified task common to all groups in the class. This permits learning from others in one's group and from other groups. Students see the design approaches used by other groups and can assess their effectiveness. They are exposed to the plethora of ideas generated by their classmates while solving the same task. They have the opportunity to learn team dynamics albeit in a limited way due to the small size of each group.

The design task must be appropriate for the students' engineering sophistication. The task must be structured so as to exploit and increase their factual and procedural knowledge while simultaneously providing experience in identifying key concepts, acquiring new knowledge and exercising judgment. Students are not expert designers, and so some information on concept identification, proving concepts, time management, setting priorities, and project management should be provided to assist them.

Finally, the task must not require extensive or expensive infrastructure. It should also be a strong motivator.

A competitive design contest is an ideal vehicle for providing these attributes. A good electrical engineering contest:

- is safe;
- makes students use and increase their factual and procedural knowledge;
- requires exercising judgment to determine appropriate trade-offs;
- fosters creativity;
- incorporates significant amounts of the material taught in other courses;
- is achievable with levels of success commensurate with design effort;
- permits many strategies leading to success at various levels;
- has significant electrical and electronics components and only simple mechanics;
- allows opportunities for students to learn from their peers;
- does not require significant infrastructure;
- can be mounted at relatively low cost;
- is easy to understand, with simple scoring;
- culminates in a spectacular tournament.

This last item should not be overlooked. The status that students gain when talking to their friends and family about the contest is an important motivator. A little 'glitz' also offers the school an opportunity for self-promotion which aids in attracting better students and raises the interest of the community.

Contest design

In order to achieve these goals, design contests should themselves be designed very carefully. The first task of the contest designer is to determine the specific goals to be achieved by the contest. Primary contest goals can include spurring creativity, teaching design for reliability, showing the engineering application of material that students have learned in the junior and preceding years, developing engineering teamwork, integrating some aspects of other disciplines into electrical engineering, etc. The contest specification is largely determined by what the instructor is trying to achieve.

Potential new contests should be evaluated with respect to the following:

- the challenge
- student assessment
- student workload
- availability of required infrastructure and support
- time required for contest management
- conformity to program goals.

The challenge

Safety. Safety is of paramount importance. Students must not be at risk of injury through participation in the contest. A primary source of danger is rapid energy release. A common #64 elastic band, configured as a slingshot, can shoot a nail into plywood because it releases its energy almost instantly. It could also blind a student and so elastics and other 'stretchies' should be avoided.

Mechanical devices release stored energy along the 'line of energy'. Students should be made aware that they must not be on the line of energy when testing their systems. Even low-power, highly-geared motors can crush fingers and tools can injure when used improperly.

Battery selection is also important for safety reasons. Sealed lead-acid and nickel-cadmium batteries have extremely low internal resistance when fully charged. They can deliver very large currents into a short circuit with the potential for battery fire and battery rupture. Care should be taken to ensure that current is limited with series fuses and series resistors.

The contest designer must ensure that all workshops and work areas are supervised. Students must not be permitted to work alone.

Scoring. A good contest should be easy to score, both so that students are clear on how performance will be measured and so the audience can follow the contest during the tournament. A good contest design will answer the following questions:

1. Can the contest be scored easily?
2. Will all heats result in at least one winner?
3. If no teams in a heat complete the challenge, how is a winner declared?
4. How are ties handled?

Solution space. The contest challenge must have a large number of solutions which are not obvious initially. This fosters inter-group discussions and the exploration of many new ideas. It also promotes the exercise of judgment and the pursuit of new factual and procedural knowledge. Questions to be addressed by the contest designer include:

1. Is the contest 'do-able' by students in junior year in a reasonable amount of time?
2. Are there many solutions to the challenge, all exploiting significant amounts of electrical engineering and requiring a range of sophistication?
3. Is it initially unclear what the winning approach should be?
4. Do all solutions require the design of at least three subsystems?
5. Is the performance of the students' solutions to the challenge likely to reflect the care and effort in design and not mere chance?
6. Are students required to use their knowledge and to gain new knowledge in the appropriate subject areas?
7. Are there multiple opportunities to exercise judgment?

Student assessment

Students are always very concerned with how they will be assessed. The assessment scheme must be fair, easily understood and easily applied. The major part of each student's assessment should be based on written and/or oral progress reports or design reviews covering the engineering work performed since the previous report. Only a minor portion of students' assessments should depend on performance during the tournament.

Students usually use the 'firefighting' method of time management, only addressing tasks when deadlines are impending. Thus, contest designers must strike a balance between requiring so many reports that students have no time to actually work on the project, and so few reports that students allow too much time to slip by before seriously undertaking the project. In a one-term contest, we find that three reports spaced throughout the term are appropriate. Reports should cover:

1. A summary, stating the kind of report, a statement of the project, the period and phase of the project covered, the problems undertaken during this period, the work completed, the work in progress, and a statement as to the future work.
2. An introduction, outlining the period and sequence of the report, the objectives of the project, the phases of the project, and a statement of which phase is being reported on.
3. A discussion section covering the problem(s) encountered in this phase, the work completed including problems and solutions, the present work ongoing, and the future work to be undertaken.
4. The conclusions, including an evaluation of progress to date, progress over this phase, and an updated project task schedule.

Each report may include test data and schematic diagrams. They should be marked primarily on the basis of engineering content (project planning, care in identifying problems, innovation in solving problems, comprehensiveness of testing, etc.) but also receive minor marks for proper format, proper use of language, etc.

Students must be reassured that they are not required to look foolish in front of peers, families or others if their systems don't work at tournament time. They must be able to withdraw from the tournament without failing the contest.

Students' workload

Poorly-designed design contests can increase students' workloads immensely to the detriment of students' marks in other courses, students' morale, and faculty support of the contest. Diversion of students' attention from other courses can be a major cause of friction within a department.

It can be very difficult to limit the amount of time students spend on the contest. The designer should select a simple task which can be completed with systems and subsystems having poor precision. This results in students getting parts of their systems operating more easily and sooner. The teaching aims are still met; students gain experience at design, but they do not need to be experts.

Easy access to the instructor and knowledgeable teaching assistants can reduce students' workload tremendously. A watchful eye on the part of the instructor and teaching assistants can be of tremendous help to the students. Without compromising creativity, these people can prevent students from spending too much time following fruitless paths or dead ends. This requires specific times set aside during which professors and teaching assistants observe students' progress, help students in difficulty, and are available for consultation.

Students frequently make use of other times for their design and implementation activities. Students appreciate being able to consult extensively with the instructor. They also find it helpful if the instructor 'drops in' to the lab many times per week outside of nominal lab hours, and if the instructor is accessible via e-mail and via a course newsgroup.

Immovable deadlines for the reports are very beneficial for students, because it forces them to pace themselves through the term. By considering mid-term and final examinations when setting report deadlines, the contest organizer can limit the impact of the contest on other courses. At DalTech, we ensure that no reports are due within one week of mid-term week, and that the tournament (the concluding event) is held two weeks prior to the start of final examinations.

Required infrastructure and support

Good teaching practice requires that an effective design contest permits the students the opportunity to test their designs prior to the tournament. Thus, any infrastructure required for testing must be available essentially from the first day of the contest, in sufficient quantity that many groups can be testing at any one time. Thus, the contest challenge must be designed to be economically viable, without requiring overly expensive materials or unavailable space.

Support costs must also be considered. At DalTech, three technologists support all the labs for all courses in electrical engineering, a total of up to 18 courses per term. With a 37-hour work week and a 12-week term, any contest cannot require more than about 74 man-hours of support per term. This figure includes time spent assisting students, making up parts kits, building the contest playfield, repairing equipment, and all other support provided to students.

Management time

Design and management of the contest is a major consumer of time for the organizing professor. He or she must be committed to the idea of goal-based learning and exposure of students to design for a successful contest. We typically spend about one month designing the challenge and preparing the necessary documentation for the students. This documentation includes a description of the contest problem, the design of the contest playfield, the set of rules, a 'what to expect' document, and a design handbook.

Considerable time is spent in consultation with students, both in lab periods and at other times. At the beginning of the contest, it can be difficult to get students to focus on the challenge. By the end of the contest, however, student consultation amounts to about 10 hours per week in addition to the lab time. On average, the organizing professor should count on spending about 7 hours per week in addition to normal lab time. If not planned for, this commitment can severely impact the teaching of other courses or research programs. With proper planning, however, the impact can be kept to a minimum.

Conformity with program goals

The contest must be designed to meet the goals of the hosting electrical engineering program or course. If the contest is the lab component of a design course, then it should employ material taught in the course as well as material from other courses. This provides a powerful opportunity for students to incorporate knowledge and ideas from other courses in their designs. A contest can provide the impetus to increase co-operation between faculty members so that contest requirements reflect the material taught in the various courses. For instance, material taught in analog electronics and DC machines are necessary for the design of a pulse-width modulated speed controller for small DC motors.

If the contest is the lab component of a particular course, then it will reflect that course material. This permits easier integration of classroom work, assignments and design work performed for the contest.

EXAMPLES OF CONTESTS

Our experiences with design contests at DalTech have included both successes and failures. Even the failures have met most of the teaching goals of the contest but may not have been as motivating or exciting for the students.

Analog electronics design competition

We have mounted a design contest at DalTech in the junior year analog electronics course for the last seven years. In this course, we promote engineering creativity, and acquisition and exploration of underlying principles. Our contests are structured to encourage students to develop systems composed of new circuits to implement their strategies.

Our contest is the annual Analog Electronics Design Competition in which students, working in groups of two, are required to design and implement analog controllers for small, autonomous robotic vehicles about 70 cm in diameter and 60 cm high (Fig. 1).

At the end of the design contest, robot vehicles compete in a double-knockout tournament on a 3.6 m by 6.7 m playing field to accomplish the tournament challenge. While the challenge is changed every year, the size of the playing field and the vehicles to be controlled have remained unchanged for the last four years.

The Analog Electronics Design Competition constitutes the laboratory part of the course in lieu of more traditional laboratory sessions. The contest requires students to design, implement and test circuitry for:

- controlling motor direction and speed
- low-level signal conditioning
- sensing light, metal, obstacles, etc.
- voltage regulation and power supply conditioning
- implementing of control strategy
- generating timing signals.

This supports the course material which includes multistage BJT and FET circuits, op-amp circuits, non-ideal op-amp behaviour, power amplifiers, voltage regulators, sinusoidal and relaxation oscillators, radio frequency circuits, tuned amplifiers, nonlinear circuits, and motor speed control.

Controller circuitry is constrained to be predominantly analog. Circuits are implemented from a standard kit of parts which contains a large variety of analog components and a few digital chips. There are no microcontrollers, microprocessors or EPROMs in the kit as this course involves analog circuit design, not programming.

To meet academic goals and to provide a basis for assessment, the contest requires three submissions of documentation on the design and implementation, including test results. The contest is worth 20 marks for the term with 15 marks based on the submissions and 5 marks derived from performance during the tournament.

A 135-page design handbook was written to partly offset the dearth of suitable material on systems design. Topics covered include:

- understanding the problem
- identifying the underlying key concepts
- generating many candidate solutions
- deciding on one solution to explore further
- implementing the solution
- evaluating the solution
- time management.

The handbook also covers many aspects of sensing, signal conditioning, motor control, etc.

A-MAZE-ing robots: the 1995 contest

One of the best contests held in recent years was called A-MAZE-ing Robots, held in the Fall of

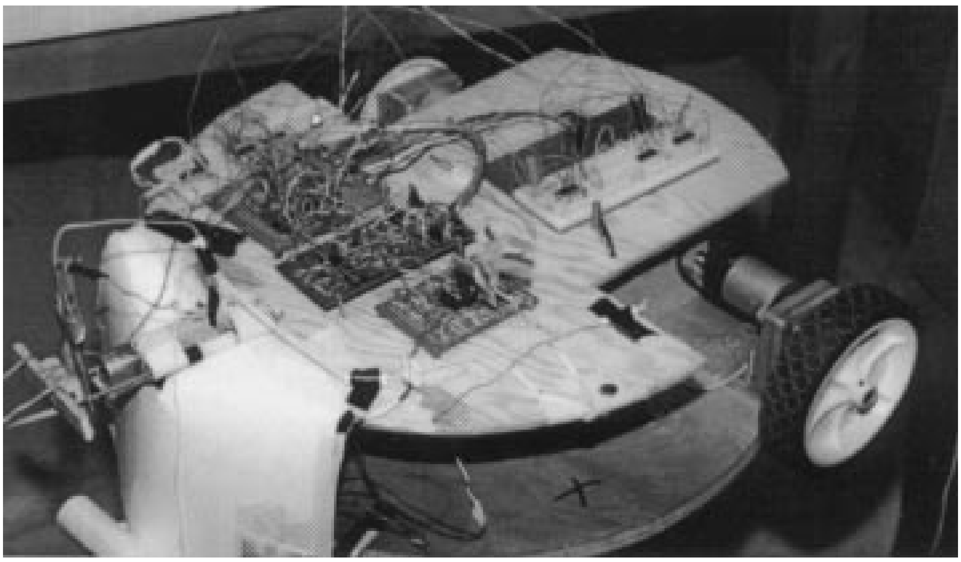

Fig. 1. The vehicle used for the contest with a controller mounted on top. The vehicle is equipped with optical triggering to start each heat, the drive motors and the batteries.

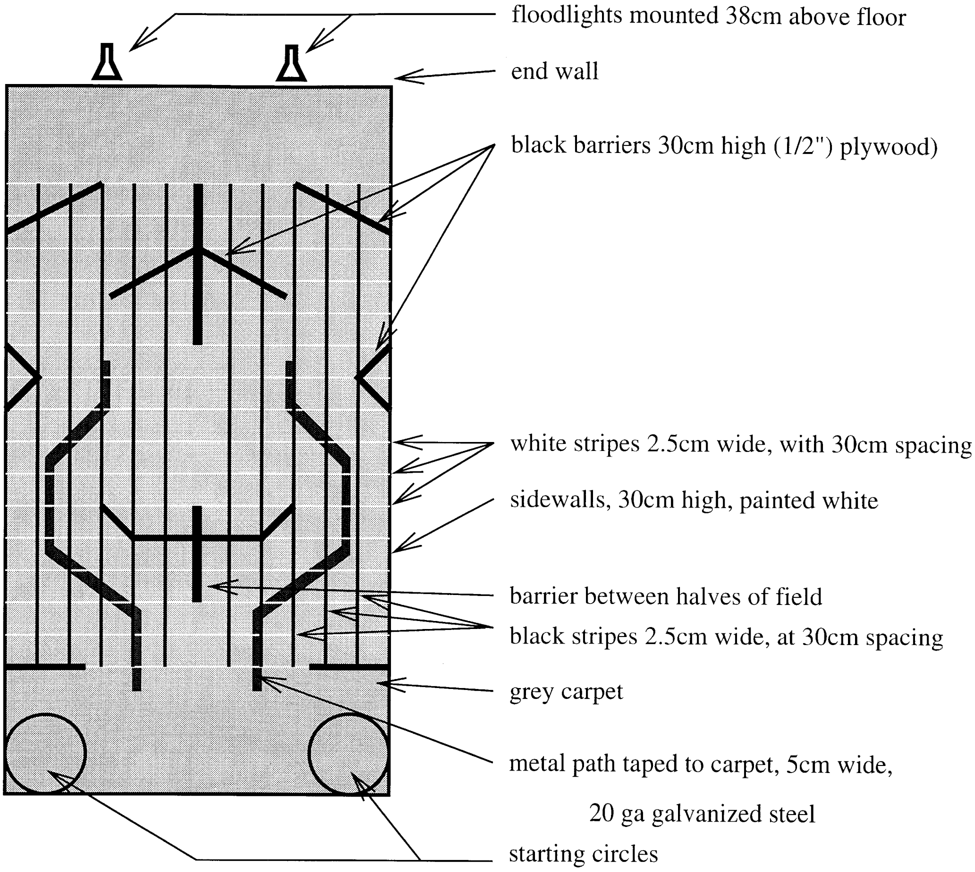

Fig. 2. The maze for the A-MAZE-ing Robots competition of 1995.

1995. Each team designed and constructed a circuit to guide the team vehicle from its starting position, through the maze to the far end of the playfield (Fig. 2). All vehicles were fully autonomous. All parts for constructing the controllers, except for resistors, capacitors, hookup wire, paints, and fastening materials were provided so that no team had an undue advantage.

The black and white stripe pairs, colours of the barriers, metal strips and flood lights permitted many sensing opportunities. The kit of parts contained components and materials suitable for implementing optical guidance, stripe counting, barrier sensing, metal sensing, and other sensing techniques.

Students' solutions to the task included dead-reckoning using timing circuits, 'wall-following' using touch and optical sensors, light-seeking and stripe-counting using optical sensing, metal-detection, and all combinations of these sensing modalities. Students found that design and implementation of metal detection systems was difficult but the performance of completed systems was extremely good. Stripe sensing proved to be prone to noise but was easy to implement, and worked well if carefully designed. The large number of sensing strategies used in various combinations suggests that students were not clear as to the 'best' way to win.

A-MAZE-ing Robots required little infrastructure (a donated carpet, halogen lights and maze components as well as the small vehicles, total cost of about Can. $1000). Most of this infrastructure is re-used each year. Since students purchase the kit of parts (about $150 per group of two), the contest typically costs about $200 per class per year. Technologists provided about 70 hours of support in setting up the playfield, in assisting during the tournament, and in assisting students with parts, specification sheets, compendia of circuits, etc. The contest provided a good spectacle, drawing a large audience (between 200 and 300 people) and the local television media.

We have been soliciting the students' thoughts on the contests for several years through a simple questionnaire administered after the contest and again one year later. From their anonymous responses, it is clear that students feel the contest to be useful for learning the material and effective as a learning tool. More information elicited from questionnaire responses can be found in [4].

Truck wars: the 1993 contest

Truck Wars was our most unsuccessful contest. The contest challenge, which took place on a table top, was to design and build an analog controller to guide a toy truck from one end of the playfield around simple barriers to the other, where it was to push a button. Circuits were connected to the trucks through umbilical chords.

This contest was not successful for the following reasons:

1. Trucks had poor traction on the contest surface, so they would not reliably follow controller signals.
2. Steering mechanisms on the trucks were insufficiently precise for reliable operation.
3. Chance played much too large a part in vehicle performance.
4. The winning strategy did not employ course material in any way.
5. Umbilical chords became tangled.
6. 'Landmarks' consisting of flashing lights were not bright enough so the tournament was held in a darkened room.
7. The playfield was too small to be easily seen on tournament night.

Nonetheless, students reported that they benefited greatly from the contest, learning more analog electronics than they would have in conventional labs.

Levitation project

Another open-ended design project offered to DalTech electrical and computer engineering students requires them to design the power circuitry, control circuitry and sensing circuitry to magnetically levitate a 0.5 kg magnetic steel C-core 6 mm below a steel plate. While not structured formally as a contest, students tend to compete with one another. This project provides most of the same benefits as a contest to the students.

As a teaching tool, the levitation project incorporates material from DC machines, control theory and electronics. Teaching features include:

- many solutions available to the challenge (state feedback, PID control, rate feedback, etc.);
- the requirement for position and velocity sensing, which can be performed in many ways;
- several methods of control (voltage or current control);
- requirement for winding design and construction;
- non-linearity of the task, requiring linearization;
- the unstable nature of the task;
- limited mechanical aspects, focusing student attention on the electrical considerations.

This project has a rich solution space, providing scope for creativity and innovation. It does not provide a spectacle in its present form, however.

The levitation project has been mounted several times with varying levels of success. As with contests, careful project design and organization is the key to success. The project is more successful if sufficient resource material is available to compensate for variations in the students' abilities, and if deliverables and deadlines are well-defined.

CONCLUSIONS

Some form of significant, open-ended, engineering design experience is required in the junior year to provide continuity of design experience throughout most electrical engineering programs. Design contests can play an important role in this regard. Contests push students to exploit their factual and procedural knowledge, to acquire new knowledge, to develop skills at identifying fundamental concepts, to improve innovation and creativity, and to improve their engineering judgment.

Good contest design must consider the following:

- the challenge, including safety, tournament scoring issues, and the richness of the solution space;
- method of assessing students;
- student's and instructor's workload;
- required infrastructure and support;
- the goals of the hosting program or course.

Care taken in contest design is necessary for a successful contest, from which students gain the maximum benefit. While the contest format, with a concluding tournament, is a major motivator for students, many of the same benefits may be gained from suitable open-ended design projects. The level of effort required to mount a suitable project is very similar to that required to mount a contest, however.

Responses from students, and our experience, indicate that design contests complete with a concluding tournament are a useful tool for teaching design to electrical engineering juniors.

REFERENCES

1. B. M. Aller, 'Just like they do in industry': Concerns about teamwork practices in engineering design courses, *IEEE/ASEE Proc. Frontiers in Education '93*, November 6–9, Washington DC, (1993) pp. 489–492.
2. J. D. Crisman, System design via small mobile robots, *IEEE Trans. Educ.*, **39**, 2, (1996) pp. 275–280.
3. R. E. Gander, E. Salt and G. J. Huff, An electrical engineering design course sequence using a top-down design methodology, *IEEE Trans. Educ.*, **37**, 1, (1994) pp. 30–35.
4. P. H. Gregson and T. A. Little, Using contests to teach design to EE Juniors, submitted to *IEEE Trans. Educ.*, September 1997.
5. A. S. Hodel, T. A. Baginski, An interdisciplinary senior design course utilizing electronically guided model rockets, *IEEE Trans. Educ.*, **38**, 4, (1995) pp. 321–327.

6. S. R. Hoole, Engineering education, design and senior projects, *IEEE Trans. Educ.*, **34**, 22, (1991) pp. 193–198.
7. S. Lekhakul, R. C. Higgins, Senior design project: undergraduate thesis, *IEEE Trans. Educ.*, **37**, 2, (1994) pp. 203–206.
8. R. L. Mertz, A capstone design course, *IEEE Trans. Educ.*, **40**, 1, (1997) pp. 41–45.

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