FIRST in Engineering: a Service-Learning Approach to Mechanical Design

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The University of Arkansas at Little Rock (UALR) formed the Donaghey College of Information Science and Systems Engineering (DCISSE) in 1999, and founded the Systems Engineering department. The first four semesters of the program expose students to a broad range of general engineering skills, including CAD, design theory, basic circuit theory and lab techniques. Students are exposed to fundamental concepts in engineering science, such as vectors, forces, dynamics, stress, and strain. The focus areas for the program, in the junior and senior years, are telecommunications and computer systems. Once these areas have been fully developed by May 2003, a control systems track is planned. Students have the flexibility to take several junior and senior level elective courses to either broaden their exposure or to attain depth in a specific area.

Systems engineering is an emerging discipline with international significance.[1] Systems engineers must not only design complex systems, they must also deploy and manage these systems throughout the global community.

Hendrix College has a program in which students can complete three years towards a BS in Physics at Hendrix and undertake the junior and senior years of an engineering program and accomplish both a BS in Physics from Hendrix and a BS in engineering from the partner school.

Within this context, a mechanical design course aimed at both Systems Engineering students and Physics students and which fulfills a technical elective is being developed. This student population does not have the mechanical analysis skills of a traditionally trained mechanical engineer. The terminology to allow communication with mechanical engineers, the attributes of the most commonly occurring mechanical elements, and tools to facilitate design decision making are the concepts which are incorporated into this course. Mechanical analysis, measurement, and prototyping are seen as equivalent sources of information, and the course emphasizes how and when to acquire such information. The student must learn how to communicate with a technician or a mechanical engineer to acquire the test or analysis.

Mechanical engineers also need to communicate with other engineers and technicians. Mechanical engineers are specialized and cannot perform all types of analyses either. Instead of stressing analysis in a design class, design skills are stressed. Therefore, this

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course is also appropriate for mechanical engineers and may be stronger than typical mechanical design courses.

Although design skills can be taught through paper exercises, in reality there are no answers in the back of the book. In order for design to truly be learned, the student must accomplish a design in reality. In the case of mechanical design, this means that an actual device must be built and tested. Although this is an expensive proposition for an engineering class, the learning experience of taking a paper design into actuality is essential to truly train an engineer.

Many design courses include a final contest to validate design skills. Contests invoke engineers' competitive nature pushing them to engage all their creativity. Contests supply an acid test to determine exactly which design is best.

Developing a design contest and providing supplies is an expensive proposition, especially for a small class. The most famous mechanical design course is MIT's 2.007 design course (http://pergatory.mit.edu/2.007/). Developing such a class is not practical at the majority of engineering programs. An alternative approach is to undertake a nationally sponsored design contest. There are many such contests, especially sponsored by ASME and AIAA.

FIRST, which stands for "For Inspiration and Recognition of Science and Technology," is a nationally prominent program whose goal is to raise awareness of engineering in society. FIRST was founded in 1989 by Dean Kamen for the purpose of pairing pre-college students with engineers from industrial sponsors. It has grown at a tremendous rate. In 2001, there were more than 550 teams participating overall and over 340 who attended the National Championship in Orlando. UALR and Hendrix College, with North Little Rock High School (NLRHS) and Pulaski Academy (PA), were involved in the FIRST program in 2000, 2001, and 2002.

FIRST has grown to international scope by involving teams from Canada and Brazil. In 2002, the first Canadian Regional event was held in Toronto, and drew 45 teams.

The FIRST competition requires the team to design and build a tele-operated mobile robot in 42 days. The robot usually manipulates balls, pushes objects, and traverses simple obstacles. Teams are supplied with a variety of motors and sensors, which they must interface with the easy-to-use, Basic stamp-powered control unit.

The majority of the challenges are mechanical or mechatronic design issues. The more successful teams dedicate a staff of five to twenty talented mechanical engineers to the problem for the design/construction phase. About 250 professionally designed, professionally built robots compete at the National Championship.

The competition structure is tailored to the industrial model. Universities have been less active in the competition, with only 30 University sponsored teams at the National

Championship in 2001. Universities recognize the skills and exposure which college-bound FIRST students possess, as evidenced by the many scholarships offered.

Several universities which have sponsored FIRST teams have published their experiences at the ASEE annual conference[2, 3, 4, 5, 6] or the Frontiers in Education conference[7]. Many of these schools, especially in the beginning, offer FIRST as an extracurricular activity. Most of this documentation is a testimonial to how wonderful the experience is. What is lacking is substantive information on how to organize a University sponsored team, training materials aimed at pre-college students, and a curriculum which includes and trains college students with diverse backgrounds in the skills appropriate to contributing to the mechanical design.

How does a University fit FIRST into its mission and structure? The challenges are:

1. Faculty resources are limited. Few Universities will devote five to twenty engineering faculty to designing a robot at the beginning of the Spring term.
2. The competition begins at the beginning of the Spring term. There is no time to educate college students in design skills simultaneous with the competition.
3. The University's mission is to train college students. Any student involvement must fit into that role.
4. Universities are not used to interacting with high schools, except as an outreach activity. Universities train teachers to train high school students. Direct involvement with students is rare and difficult.
5. Training materials specific to FIRST are not widely available.

There is a growing trend in engineering education, which may solve many of these challenges: service learning. Service learning identifies a community need and designs service activities to address the need.[8] Students' skills are acquired in "structured educational components" of a course and are applied to address the community need. It has been reported that service learning, when properly articulated, can address issues of student apathy, lack of engagement, and inability to complete a project.[9] Usually engineering service learning is applied to developing products to improve conditions for the handicapped.[10, 11, 12] The community need addressed in this paper is motivating and preparing pre-college students for training in science and engineering.

A service learning based course must incorporate several critical components.[9] Academic credit must be assigned only for the educational components of the course and not for the "extra work" imposed by the service. The service facilitates learning, much like homework. The educational goals and the service expectations must be clearly articulated for both the students and the beneficiaries of the service at the beginning of the course. The educational goals must be assessed according to a standard comparable to the same academic material delivered in a traditional fashion. The quality of the service must also be assessed, and feedback from both students and the beneficiaries of the service must be provided.

UALR and Hendrix have attempted two different models for incorporating college students into the FIRST team. The first attempt, at the 2000 competition, added a special section of Introduction to Systems Engineering (a Freshman introductory course).[13, 14] This course was similar in form to that offered by U. S. Coast Guard's program.[4] Five UALR students and one Hendrix student participated in this course. Although the course met with limited success, it illustrated many of the pit-falls associated with connecting an introductory course with FIRST.

We assumed that the pre-college students on successful FIRST teams were performing some useful role in the design process. Therefore, Freshmen engineering students should be able to participate. In reality, most corporate teams assign a large engineering staff to perform the design and allow their pre-college students to "shadow" the engineers. The younger students are much better suited to construction and testing tasks, following the directions of the engineers.

The two students (one from UALR, one from Hendrix) who succeeded in the course were not Freshmen. The UALR student was a Sophomore level transfer from the Engineering Technology program. The Hendrix student was a senior in Physics. These students were mature, possessed some relevant skills, and were confident enough to attempt tasks and learn from their mistakes.

The FIRST competition starts in January, shortly before the beginning of the Spring semester. Freshmen do not have time to develop engineering skills before they need to apply them. Further, the Freshmen engineering students reflected the national trend for incoming students.[9] They were apathetic, lacking in motivation and time management skills, and unable to get started. Although there was a stated expectation that the college students were required to interact with the high school students, only the two successful students helped the high school students.

The successful UALR student returned to the 2001 and 2002 teams, despite receiving no academic credit for his efforts in 2001 or 2002. He volunteered to set up practical electronics training courses for the high school students for Fall 2002 and is one of the instigators for the ideas set forth in this paper.

The lessons learned in year one were:

1. Freshmen must learn engineering and time management skills before participating in FIRST. The experience is too intense and time-consuming for Freshmen to serve as the technical leaders.
2. The interaction with the high school students must be graded to get the maximum advantage.
3. The Freshmen who took the FIRST section of the Introduction to Engineering course received a much better introduction to the engineering profession than the regular section.
4. Typical high school students have few manual skills, do not know how to use engineering software, and are not prepared to undertake a designing role. They can be taught many of these skills. However, the short building phase does not allow enough time for students to both learn and apply the necessary skills before the project deadline.

5. Training and team-building must start in October to prepare for January's kick-off.
6. Academic credit must be offered to get sustained college student participation.

The second attempt, at the 2001 competition, used Mechanical Engineering Technology's senior design class. This class normally performs a design for a local industry customer. The FIRST project was the 2001 class's customer. Five students participated in the class.

The value of this program can be seen through a specific example. One of the students designed the primary drive system. Originally, a treaded design, using a timing belt as a tread, was chosen. Tread slip is a known problem with this type of design, since a timing belt was not designed as a traction element. We had successfully designed this type of system the previous year, so we thought we were prepared.[15] Due to differences in weight, contact area, and tread wrap, the new design experienced a pronounced tread slip problem. After attempting several fixes, we chose to go to a differential, chain-drive configuration due to time constraints.

At the National Competition, about 25% of the entries had chosen a treaded configuration. All of these had experienced the same problems, and many tread slip solutions had been found. The student, who had attempted the treaded design, approached and discussed this problem with these teams. For every design element, whether successfully or unsuccessfully accomplished, at least 100 other, successful designs will be present at the National Competition. Due to the student's intense focus on a problem, he is prepared to communicate and understand the details of the other solutions, and he is receptive to learning the other approaches.

The lessons learned in year two were:

1. The good senior design students were capable of contributing design details to the project in a timely fashion. However, it is rather late in the student's career to gain the full benefits of the program. Ideally, the student will have another year to benefit from additional university training.
2. The high school students still did not play a big role in the design process. They need to be trained prior to the start of the competition. Skills which high school students and Freshmen can master include basic machine shop operation, operation of test equipment, operation of CAD and visualization software, basic wiring and soldering, and controller programming.

There is an enormous potential for involvement of college students in the FIRST activity. The primary obstacle is developing a model which fits into the University's academic paradigm and which matches with the FIRST objectives and strengths. This paper sets forth a possible model, which adapts efforts at other universities and which builds on the lessons learned in UALR's and Hendrix's first two years of FIRST participation.

Curriculum

The course is split across two semesters. The first semester is lecture and training, and the second semester is the design competition. The two course sequence is named FIRST in

Engineering I (three academic credits) and FIRST in Engineering II (one academic credit). The first course is prerequisite to the second course.

The sequence provides an activity where engineering students can practice their skills in a real project environment. It provides some hands-on engineering activities. Since part of an engineer's experience in industry is to train young engineers in the discipline, a service learning activity for engineering students is provided.

Course Descriptions
FIRST in Engineering I. Fall semester only. Junior level. Three academic credits. Three hours per week of lecture/practicum and two hours per week of service.

Contact hours consist of lectures, interspersed with practical demonstrations of the principles outlined in the lectures. The demonstrations require that students interact with the demonstration, after the fashion of a laboratory. The machine shop training occurs separately from the lecture.

Lecture material: indicial notation, coordinate systems, strain, stress; material properties and isotropic constitutive laws; failure: yield, fatigue, buckling; friction; mechanical elements: fasteners (screws, rivets, welds), bearing surfaces (bushings, bearings, lubrication), power transmission (pulleys, chains & timing belts, gears), shaft couplings (set screw, key, Woodruff key, spline, couplers); basic operation and mounting of DC motors; basic operation and mounting of sensors (potentiometer, switch, yaw rate). Advanced students will be given the opportunity to independently study the finite element method, or computer aided manufacturing and CNC.

Practicum material: machine shop operation (drills & taps, drill press, band saw, lathe, mill); how to create a solid model using a caliper and a CAD program; how to measure friction; beam bending using strain gages to measure surface stress; demonstration of motor driven power transmission elements, including measurement of losses; demonstration of positional control.

Homework exercises consist of case studies from previous designs. For example, static analysis of scissor mechanism, design of planetary gear stage, bending analysis of cantilevered shaft, acceleration analysis of drive train. Each case study has the actual mechanism available for comparison. Other exercises include development of engineering data to support competition objectives, such as dimensional measurement of components and development of solid models, measurement of traction material friction coefficient, development of torque-current curves for motors, measurement of gearbox efficiency, and reverse engineering of mechanical components (including determination of functional requirements). Since engineers must communicate ideas through writing, each homework assignment reports results through a memo.

Service: The high school students receive training in basic machine shop operation, basic electronic fabrication, use of CAD software, and engineering measurements. The college students meet with the high school students for one hour, twice a week to perform this training.

Assessment: The majority of the grade is determined by exams on analytical material, homework, and class participation. The service component is graded pass/fail. Failure on the service component deducts one letter grade. In other words, if a student qualifies for an A based on exams, homework, and class participation but fails the service component, he earns a B.

Assessing the Service Component: The goal of assessing the service component is to determine whether college students have effectively passed knowledge to the high school students. This will be affected by the relationship between the college and high school students, the mastery of the material by the college students, the prior skill level of the high school students, and the motivation of the high school students. It is important to null out the variability in the high school students' backgrounds from this assessment. A skills survey of the high school students is done at the beginning of the training. This consists of yes/no answers to questions, such as "Can you drill a hole with a drill press?" If the student answers "yes" to any questions, he will be called upon to demonstrate his ability, and the result will be assigned a numerical grade (0-100). Upon completion of the training program, the high school students demonstrate all elements of the skills survey, except for those on which they received a 90 or above on the entrance skills survey. They indicate which college student trained them on each skill. A difference between the entrance skills survey and the exit skills survey for each skill, weighted by a difficulty factor for that skill, is calculated. A histogram for each student is computed. This histogram represents the student's progress profile.

Students who exhibit a peak at the low end of the spectrum must be considered carefully. If the student was trained by several college students, his poor performance may have resulted from his deficiencies, and his scores are thrown out for purposes of determining college students' grades. If he was trained by one or two college students, his performance may have resulted from poor training, and his scores are used in the college students' grades.

A histogram for each college student is generated. Those which exhibit a Gaussian distribution will have an average computed and compared against a threshold. Those above the threshold pass. Those below the threshold receive a fail. Those histograms which exhibit a non-Gaussian distribution will be judged on an individual basis. For instance, a binomial distribution could result when a college student masters the machining skills but fails to master the CAD skills. If a college student attended all the service sessions, but never trained a high school student in any skills or if a college student did not attend the service sessions, he would fail.

FIRST in Engineering II. Spring semester only. Junior level. One academic credit. 3 contact hours per week for the first six weeks of the semester. To participate in this course, a student must receive a C or better in FIRST in Engineering I and must have passed the service component.

The project part of the mechanical design course will begin immediately following the FIRST kick-off meeting. The first three to five days are used to digest the rules and brainstorm a strategy. The top level functional requirements for the robot are determined. The group subdivides into smaller design teams (two-three students). One team is devoted to the drive system. One team is devoted to the controller and electronics systems. The other functional requirements, which will vary from year to year, will have two or three teams assigned to each, where the teams are working on different approaches to satisfy the same functional requirement. Contact hours will consist of progress reports by the design groups, design advice, and consultation.

Each group determines second level functional requirements, develops a design configuration, analyzes and simulates to refine the design configuration, and presents the final configuration at a design review three weeks into the competition. The configuration which appears most promising for each top level functional requirement is chosen for final design and manufacturing. The configurations which are not chosen are terminated, and students on terminated projects are chosen by the continuing teams. Students who are not chosen are assigned non-critical tasks.

Service: Throughout the design process, the teams are brain-storming, measuring component attributes (such as friction, motor torque, sensor outputs), preparing CAD models and assemblies, and building prototypes. The high school students learned these skills in the previous semester. The high school students come to UALR two days a week for two hours and on Saturday for the entire day. The design teams are expected to draw on this labor pool to assist in their design and manufacturing process. Relationships will have formed in the first semester between the college students and the high school students. Those high school students who are more reliable will tend to be recruited onto a specific design team, rather than being assigned daily work.

Assessment: Grades are assigned based on an accumulation of points. Points are assigned for the weekly group progress reports, individual contribution to in-class discussion, the group design review, the individual final report, and the service. Students whose projects are terminated at the three week point and who are not chosen for another design team will have fewer chances to earn points, and will therefore earn lower grades.

Assessing the Service Component: The goals of the service is to create an interaction between the college and high school students and to provide supervision and training of the high school students. There are eighteen work sessions during the 42 day competition. At the end of each session, each design group will complete a survey for each task assigned to each high school student. The survey will indicate who assigned the task, quality of the outcome, amount of intervention required, and who intervened. Students will gain points for service based on number and difficulty of successfully completed tasks and based on successful interventions.

Conclusion

FIRST provides an unparalleled opportunity to advance mechanical design education. The main barriers include the inconvenient starting time, the short design time-line, the lack of prepared educational materials, and the difficulty of reconciling the university's educational goals with the service to the high school. This paper presents some ideas on how to overcome these barriers.

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