FIRST in Engineering: Elements of Mechanical Design

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The role of design in engineering education and the teaching of design has changed over the past several decades. In the specific case of mechanical design, increasing emphasis has been placed on mechanical analysis rather than on design methodology. This can be seen in the dominance of mechanical analysis in mechanical design or machine design textbooks and the relatively light (or non-existent) treatment of how to make design decisions. The reasons for this trend have been described in Suh's Principles of Design[1] and Hazelrigg's Introduction to Systems Engineering[2], among others.

There has been a growing trend to re-examine what skills are taught in a design class. This trend is driven primarily by industry's need for project management and design decision-making skills, in addition to analytical skills.[3]

Another skill set which has been disappearing is design by analogy. Emphasis is placed on developing novelty in design (the "new and different"). In fact, a "new and different" design requires complete validation, which is more expensive than modifying an existing design to achieve new objectives. The costs of validation and reduction to practice must be considered in the decision to develop a new design versus modifying an existing design.

With the development of optimization methods and more powerful analytical tools, many engineering students suffer under the illusion that, with enough mathematics and computing power, the design process requires only that constraints be established, and a computer will compute the answer. However, design is a synthesis process, and it is not possible to calculate a unique design. In general, the constraints are never fully known, and they change over time.

The designer must develop a skill set to evolve through the infinities of solutions to synthesize one out of many successful configurations. Since design is a creative process, it is very similar to the process of music composition. The composer must first learn the standard musical forms. He then combines those forms with his creativity to synthesize a novel composition. The design equivalents to musical forms are the elements of design. A first design course should introduce these elements and demonstrate the "process of composition." The analysis of the design should come later.

This is not to say that analysis and engineering science are bad things. In the modern world of developing technology, new technologies can only be created through the combination of science and engineering. The student needs additional training in failure analysis, kinematics, dynamics, and many of the other techniques common to mechanical engineering before he can call himself a mechanical engineer.

Nonetheless, there are other skills which must be taught in addition to engineering analysis. Knowledge of common mechanical elements and how to combine them can carry a student quite far in the world of design. A design course which can allow the student to prepare configurations for later analysis is an excellent starting point on the road to becoming a designer. This enhances the later analysis activities. There are enough of these skills to fill an entire course, and these skills are more accessible to non-mechanical engineers than those conveyed in a typical mechanical analysis driven design course.

If students can first evolve configurations, the analysis skills have a context in which to develop. The question, "If this rivet is subjected to 100 N load, will it fail," is not as compelling as the question, "Will the rivets in your robot arm hold under worst case loading conditions." In the first case, the student answers the question and forgets about the technique until he must use it later in practice. In the second case, the student actually cares about the answer, since it may mean the difference between his device succeeding or failing.

In the Spring of 2002, the University of Arkansas at Little Rock offered a mechanical design course which was aimed at both Systems Engineering students and Physics students. Since this student population does not have the mechanical analysis skills of a traditionally trained mechanical engineer, the course was designed to focus on design methodology, attributes of a broad range of mechanical elements, and rudimentary analysis. 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. [4]

Although design skills can be taught through paper exercises, in reality there are no answers in the back of the book. 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 in engineering training.

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 sponsored by organizations such as ASME and AIAA.[5,6,7]

FIRST, which stands for "For Inspiration and Recognition of Science and Technology," is an internationally 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. UALR and Hendrix College, have been involved in the FIRST program in 2000, 2001, 2002, and 2003.

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. Several universities which have sponsored FIRST teams have published their experiences in a variety of ASEE publications[8,9, 10, 11, 12, 13, 14].

The majority of the challenges involve mechanical design. However, recent changes in the contest incorporate more sensor and software challenges. The contest is becoming a proving ground for mechatronics design.

The ideal FIRST team consists of partners from local high schools, a university, and an industry partner. Wilczynski, et al., provide an excellent overview of the benefits to the high school beneficiaries and to society for supporting a FIRST team.[8] Although there are many benefits for either the University or Industry partners, each entity must determine how this service can fit into its mission.

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.[15] 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.[16] The community need addressed in this paper is motivating and preparing pre-college students for training in science and engineering.

The FIRST competition starts in January, shortly before the beginning of the Spring semester. Due to the short time frame and the pre-semester start, it is not possible to teach skills and then have the students practice them. Therefore, the design course has been split across two semesters. The first semester is lecture and training, and the second semester is the design competition and is structured like a laboratory. The two course sequence is named FIRST in Engineering I (three academic credits) and FIRST in Engineering II (one academic credit).

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, the service learning activity of training their high school mentorees gives students a head start in developing management skills.

FIRST in Engineering I was offered in Fall 2002 to a small class. The first two weeks of lecture material (see http://theduchy.ualr.edu/classes/asci53xx/syllabus.html for the class notes) covered the basics of brain-storming and project management. Conceptual design theory (functional requirements and design parameters) was introduced. Several brain-storming activities were conducted to illustrate the iterative and hierarchical nature of the design process.

Power transmission is a vitally important concept in the FIRST competition. Methods for achieving power transmission and some of the analysis techniques to determine the effectiveness in a design were introduced. Pulleys, chains, and timing belts were covered in brief. Considerable focus was applied to gears and gear design. Spur gears and worm gears were the main topics covered. The advantages and disadvantages of the different types of power transmission are discussed, along with situations where each is the correct solution. Examples are drawn from previous FIRST robots, and the actual systems are disassembled and explained.

Fasteners were covered. The situations where each type of fastener (screws, rivets, welds) should be used were described. Basic strength of fastening and number to use for each application were described. Issues of assembly and disassembly and cost were covered. Students were advised to use the correct size fastener consistent with the tables in Machinery's Handbook, based on load condition, rather than performing detailed stress calculations. Shaft couplings (set screw, key, Woodruff key, spline, couplers) were also described in this section of the course.

The different bearing surfaces (bushings, roller bearings, and lubrication) were explained. Since many FIRST applications require the proper support of shafts and the proper bearing surface for a variety of loading and speed conditions, there are many examples from past robots available for study.

Almost every mechanism on a FIRST robot requires a motor or pneumatic piston to drive it. Mounting of motors, protecting motor shafts from side loads, and creating proper cooling were described. Due to student interest, extra material on basic function of DC motors was prepared.

Since most FIRST mechanisms require some feedback for proper operation, basic operation and mounting of sensors (potentiometer, limit switch, photoelectric switch, and yaw rate sensor) are covered. FIRST is relaxing its rules on sensors and allowing more options. As these options become available, they will be included in the course. For instance, this year's robot uses encoders to perform odometry in the autonomous phase.

Service and Mentoring:
The FIRST in Engineering class mentored students from North Little Rock High School (NLRHS). This school is an urban school with lower income and at risk students. In the Fall semester, NLRHS participated in the BEST (Boosting Engineering Science and Technology) competition. The BEST competition requires that the high school students perform all the design and fabrication. The FIRST in Engineering students led brain-storming sessions and guided the high school students through the design process. The FIRST in Engineering students motivated the design groups and kept them on target.

The high school partner decided to design a mini-robot which would cross a ramp and pick up a bouncing "bumble-ball." The college students provided assistance in drive system calculations and in the design of the ball pick-up.

The robot had to accelerate on a flat surface and then climb a steep hill. Given limitations in materials, the best mini-robot design used two motors direct-driving the wheels. The only free parameter was the wheel diameter.

This exercise took the students through DC motor specifications, the relation between voltage and speed in a DC motor, and static analysis of a simplified vehicle on flat surface and on a slope.

The college students developed equations of motion for the robot, which included the motor's torque versus speed equation. They simulated these equations and determined the optimum wheel diameter. The students picked a wheel diameter and the device was built.

The initial tests indicated that the speed was much slower than predictions. It was discovered that the motor specifications were developed for a 12V power supply and the robot power supply was 7V. Once this correction was made, analysis and experiment matched within the losses imposed by the wheel mounting.

At the conclusion of the BEST project, the college students continued to train the high school students in CAD and basic design skills. The mentoring relationships which developed in the Fall semester are continuing in the Spring semester as the team designs and builds its robot for the FIRST competition.

The first design project in FIRST in Engineering I was to design a box to house the robot controller, connectors, and provide protection from shocks and falling objects. This was primarily an exercise in learning what fasteners were available and how to use them. It also required the students to refresh their CAD and assembly skills.

The final design was to develop a linkage to hook a schedule 40 aluminum pipe. Many FIRST contests have involved grabbing heavy things and pulling them. An effective design was observed at the 2002 competition. The students wanted to design their own version of this mechanism. It used a slider-crank which had a toggle point such that, when the claw was closed, it could only be opened by pulling the slider back. Pulling the claw back or pulling the object away from the claw actually increased the claw holding power. The students ran into difficulties at the end with the mechanism synthesis. However, a successful demonstration prototype was developed.

FIRST in Engineering II.

The project part of the mechanical design course began immediately following the FIRST kick-off meeting on January 4, 2003. The first five days were used to digest the rules and brainstorm various strategies.

The FIRST in Engineering II class, which started as this paper was being written, chose to design a mechanism which could pick up storage bins and stack them. The students finished the CAD models and had the design complete in one and a half weeks (see figure 1). This design included not only the mechanical systems, but also the actuators (two motors and two pneumatic pistons) and the sensors (two potentiometers and a yaw rate sensor). The picture of the stacker mounted on the entire robot is shown in Figure 2.

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.

Dr. Andrew Wright, during his stay in industry and during his time teaching in the graduate program at UALR has interacted with dozens of engineering graduates at all levels (B.S., M. S., and Ph.D.). These graduates uniformly lack even the most basic design skills. The students who have passed through the FIRST in Engineering class and who have actively participated in UALR/Hendrix's FIRST program have demonstrated the abilities to design, build, and test complex mechanisms. The methods outlined in this paper are effective, and the graduates are increasingly valuable to both industry and academia.

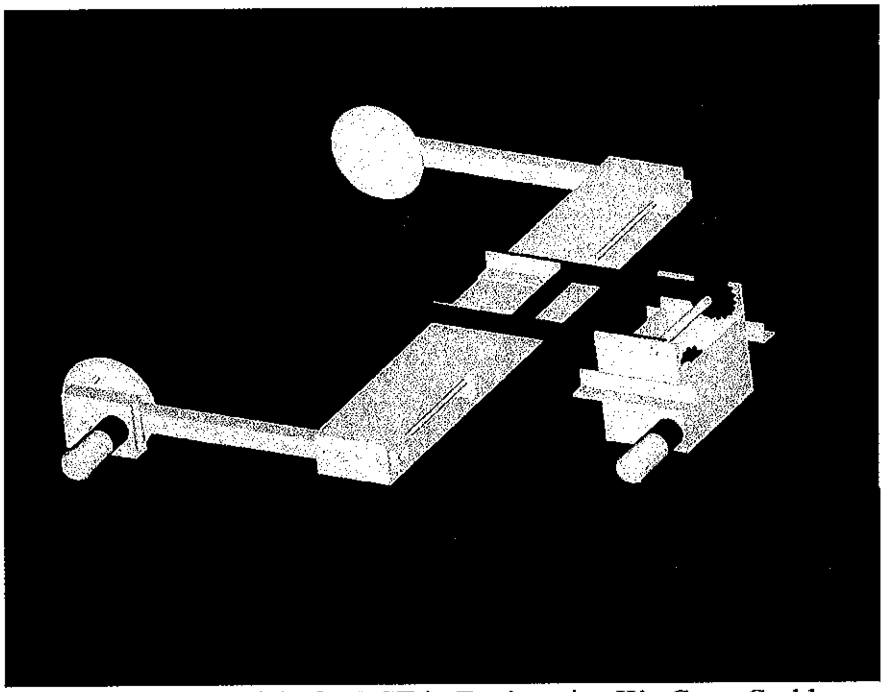

Figure 1. CAD Model of FIRST in Engineering II's Crate Grabber and Stacker

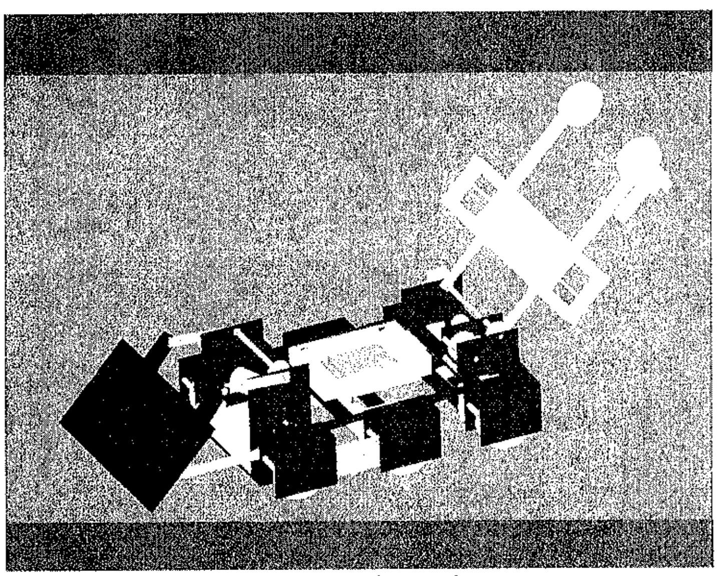

Figure 2. CAD Model of Entire Robot

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Biographical Information

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