Striking a Balance: Bringing Engineering Disciplines Together for a Senior Design Sequence

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Abstract

Historically, the essence of engineering is the act of creating products to improve society. More than ever, today's engineers are expected to work across disciplines to design increasingly complicated products. At the University of Missouri-Rolla, we have introduced an interdisciplinary design curriculum to teach core engineering design skills across departmental lines (electrical and computer engineering; engineering management; and mechanical engineering) while simultaneously utilizing individual engineering disciplines within systems-level design courses.

The format of the interdisciplinary design curriculum is a two-semester senior year sequence. In the first semester, engineering design theory and methodology is covered. Hands-on projects give students an immediate avenue to actively experiment with the design topics through reverse engineering and redesign projects and an original design project. Project management and teaming skills are covered during the first semester as well. With design tools and methods in hand from the first semester course, student teams in the second semester projects course complete a semester long project and produce a working prototype. This year the project is sponsored by an Army advanced technology group that provides a prototyping budget and technical review services. In addition to weekly lectures, student teams work with one, or possibly several, faculty advisors from appropriate departments who serve as technical experts for the project.

The interdisciplinary design curriculum pushes design education to more accurately reflect current engineering design practice in today's technological workplace. Over the history of engineering, the engineering education pendulum has swung between the extremes of a vocational, apprentice-like education and a strict, theory-based engineering science approach. The design curriculum proposed here is our attempt to strike an appropriate balance between engineering science and the ability to produce physical artifacts.

1. Introduction

Today's product design engineers are expected to work across disciplines to design increasingly complicated products. However, design courses in most US universities teach design within a specific discipline. At the University of Missouri-Rolla, we have initiated an interdisciplinary design senior sequence that more accurately reflects and prepares students for product design roles. Interdisciplinary design courses are not new; many such courses were available in the 1960s and 1970s (Lovas and Packman, 2001). Example programs at institutions such as Rensselaer Polytechnic Institute, Lehigh University, University of Detroit and Northwestern University brought engineering disciplines (and sometimes non-engineering disciplines) together to solve societal issues related projects under a program funded by the Sloan Foundation. Since that era, government and accreditation agencies have identified the lack of interdisciplinary design experience and capabilities as a major stumbling block in improving engineering education (NSF 1996a & b; ABET, 1997). Today interdisciplinary design courses are appearing again to answer that need (45 papers have documented interdisciplinary design courses over the past 5 years of ASEE conferences), but are still the minority occurrence.

In addition to providing a realistic design experience, our interdisciplinary design sequence gives students the skills *to design*. Capstone design courses are often administered as simply a project course with little or no formal design theory and methodology. In some cases this leaves students with the false impression that design is not an important skill, or worse, that design is not "teachable." By presenting formal design theories and methodologies, engineering students learn how to design a product (Otto et al., 1998).

As students learn how to design, production of a physical artifact is essential. Unfortunately, undergraduate engineering education has long divided learning activities into lecture and hands-on laboratory courses, with lecture courses greatly outnumbering lab activities. Learning theories and studies on learning and teaching styles indicate that integrated lecture and laboratory activities are better suited for complete learning (Kolb, 1984; Wankat and Oreovicz, 1993; Stice, 1987; NSF, 1996; Felder and Silverman, 1988). Many courses have applied these learning theories to their courses by adding hands-on activities to supplement the theory (Agogino, 1992; Carlson, 1995; Hibbard & Hibbard, 1995, Niku 1995, West et al., 1990; Otto et al., 1998). Other courses, such as mechanical dissection by Sheppard (1992) and reverse engineering by Wood & Wood (2000), encourage students to "tinker" with products in an effort to aid their understanding of physical systems and to provide an enjoyable learning experience. We extend and apply these concepts to our interdisciplinary design course.

2. Course Overview

The interdisciplinary design curriculum offered through the Basic Engineering Department represents our attempt to provide a senior design experience that accurately reflects product design in today's technological workplace. Historically, the essence of engineering is the act of creating products to improve society. More than ever, today's engineers are expected to work across disciplines to design increasingly complicated products. Our curriculum teaches core engineering design skills across departmental lines while simultaneously utilizing individual engineering disciplines within a systems-level design course.

2.1 Format of the Interdisciplinary Design Courses (BE220 & 301)

The format of the interdisciplinary design curriculum is a two-semester senior year sequence. In the first semester, engineering design theory and methodology is covered (as a three credit hour course). The second semester course is a project course (three credit hour) with lecture content focusing on embodiment issues such as prototyping and manufacturing.

Engineering Design Methodology: the First Semester

During the first semester course, six topic areas of engineering design are covered. Our approach emphasizes systematic approaches to the design of any product. It also entails some "re-wiring" of the students to draw on and develop their own creative skills. This is perhaps the greatest challenge we face with our students. After three years of math, science and engineering science courses, it takes a concerted effort (and repeated reassurance) to convince students that it is acceptable for a problem to have more than one answer and to explore creative solutions. We address these issues through team activities and hands-on creativity exercises, which are discussed in later sections. The six topic areas we cover are listed below in Fig. 1 and a sample syllabus is included in Fig. 2.

Topic 1:	Engineering design as a process: Types of design: original, parametric, redesign, reverse engineering; Team work, creativity; Simple design examples.
Topic 2:	Problem/project clarification and specification: Project timeline planning; Gathering customer needs; Transforming needs to engineering specifications; Benchmarking.
Topic 3:	Functional decomposition and concept generation: Function structures; Solution principles; Search techniques; Product architecture; Concept variants.
Topic 4:	Preliminary design tools and concept selection: System models of concept variants; Concept screening; Decision matrices.
Topic 5:	Embodiment design: Reverse engineering; Concurrent engineering; Design guidelines, design for manufacture; Prototyping.
Topic 6:	Product Evaluation: Parameter design; Design of Experiments; Robust design (Taguchi method); Sensitivity analysis.

Figure 1. Topic areas covered in the design methodology course.

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BE 220 Engineering Design Methodology - Syllabus
University of Missouri-Rolla, Fall 2001
Text: *Product Design: Techniques in Reverse Engineering and New Product Development*, K. Otto and K. Wood, Prentice Hall, 2000.
Reference Text: *Engineering Design: A Systematic Approach*, G. Pahl and W. Beitz, Springer Verlag, 1996.

Week	Date	Topic	Reading
1	Aug. 20	Overview: original design vs. redesign; MBTI analysis; Team building exercises	Chaps. 1-2
2	27	Creativity techniques; Reverse engineering methodology; Customer needs	Chaps. 3-4; Handout
3	Sept. 3	Functional modeling: function structures	Chap. 5
4	10	Cause and effect diagrams: fishbone structures; Disassembly: BOM, exploded view, subtract & operate procedure	Chap. 6
5	17	Solution principles (Morphological matrix); Transforming customer needs to engineering specifications (QFD); Benchmarking	Chap. 7
6	24	Concept generation **Project 1 due: Sept. 28 at 4 PM**	Chap. 10
7	Oct. 1	Functional modeling; Concept generation	Handout
	5	*Student Council Free Day* (Friday)	
8	8	Product architectures; Design by analogy	Chaps. 8-9
9	15	Concept screening; Decision matrix ; Decision making: Systems modeling	Chap. 11
10	22	Decision making; Systems modeling	Sects. 13.1-5; Chap. 16
11	29	Reverse engineering: embodiment steps **Project 2 due: Nov. 2 at 4 PM**	Chap. 12 & 17
12	Nov. 5	Design of experiments	Chap. 18
13	12	DFM, DFA	Chap. 14
14	19	Design for Environment	Chap. 15
15	26	Robust design	Chap. 19
16	Dec. 3	Product architecture-based teams; Original design review; Transition to BE301 **Project 3 due: Dec. 7 at 4 PM**	
17	10	Finals Week	

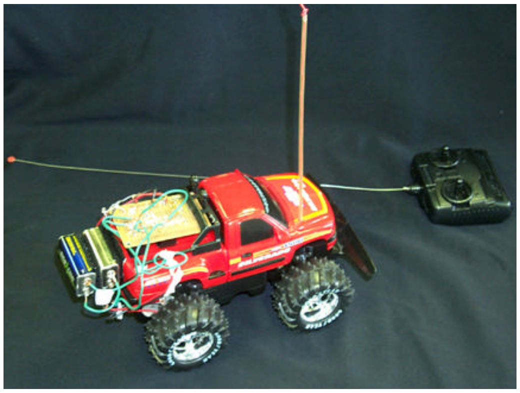
Figure 2. A sample syllabus for the design methodology course.

Looking more closely at the six topic areas in Fig. 1, the basic design initiates the semester with new topics for all of our disciplines (Topics 1-3). The abstract design concepts and emphasis on creative problem solving is generally new territory to students (or at best a vague memory) and tends to grab their attention up front. The engineering management students do have a slight advantage with project planning in Topic 2 and this helps ensure that the initial project stays on track. As we move into Topics 4 and 5, students are expected to draw more from their individual discipline-specific engineering sciences courses. Specifically, engineering model formulation and solution/simulation skills are emphasized in Topic 4 and manufacturing skills are utilized in Topic 5 (our mechanical, electrical and computer engineering and engineering management programs all contain discipline specific manufacturing content). Near the end of the semester, Topic 6 features design and analysis techniques that are generally new to all disciplines

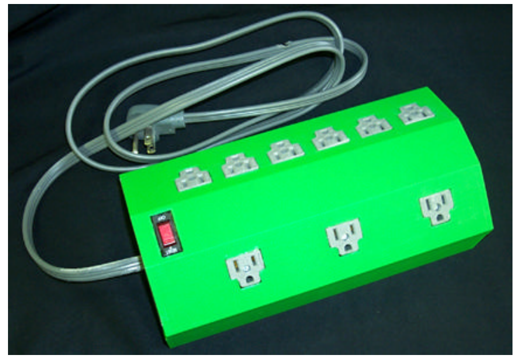
The design methodology course is a project driven course. Three team projects are completed during the semester. The first project is a reverse engineering project where students select a consumer electro-mechanical product for redesign. Here the students carry out steps 1-5 of Otto and Wood's reverse engineering methodology (Otto and Wood, 1998). Doing so exposes the students to the concepts of gathering customer needs, deriving a functional model of the product, disassembling the product, generating a bill of materials, identifying solution principles for the product's functions and benchmarking the product through completion of a Quality Functional Deployment (QFD) chart. Many of these concepts are rather abstract and presenting the techniques just in time for the students to apply them to their product provides an immediate concrete experience to assist in learning. At the end of the first project, students have a good understanding of how the existing product operates and what system (or sub-systems) need to be redesigned to meet customer needs.

The second project is an original design of a "new" product. Here the students again start by gathering customer needs, deriving a functional model and completing a QFD chart. Additionally, they practice the new techniques of concept generation that we teach as morphological analysis, product architecture definition and design by analogy. Creative concepts are encouraged at this point as students are taught creative concept generation techniques such as brain ball, mind maps and the 635 method (Faste, 1992 & 1994; Wilde et al., 1994; Faste et al., 1993; Otto and Wood, 2000). Additionally, we introduce them to physical and drawing exercises designed to stimulate the right brain (which is associated with creativity) (Edwards, 1999). Finally, the engineering science courses are brought into the picture as students derive mathematical equations to model each concept variant's performance. The mathematical models allow quantitative criteria along with qualitative criteria to be used to select the concept to embody. Screening techniques such as a Pugh chart are used to eliminate infeasible variants early and more sophisticated selection techniques such as a decision matrix are used to make the final selection. This original design project also serves as the lead in to the second semester course. The same project is continued in the second semester design project course and the bulk of the up front work of needs gathering is, thus, already completed. More detail about our specific Smart Marker project with the US Army is provided in Section 3.

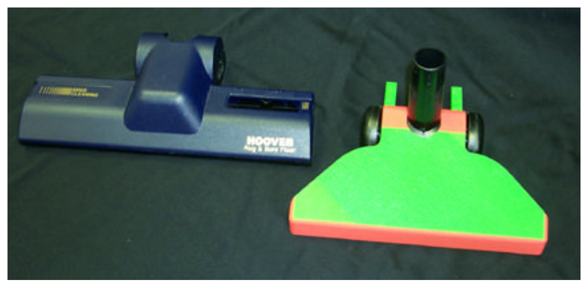
For the third project, we return to the product redesign introduced in project 1. Here the teams complete the embodiment phase by making appropriate mathematical and physical prototypes to specify component changes to the existing product. This involves completing steps 6-10 of Otto and Wood's reverse engineering methodology. Along with a final report, the students produce a working prototype of their redesigned product. Example products in the fall 2001 semester are shown in Fig. 3. Prototyping efforts ranged from new (more powerful) components in the radio controlled truck to redesigned attachments for a Hoover vacuum to a completely new body and layout of a surge protector power strip (both the vacuum and the power strip utilized Stratasys rapid prototyping machines on campus).



(a)
The remote control truck team adaptively redesigned their product to add a more powerful motor, a separate motor controller and additional power source. They also parametrically redesigned the steering sub-system to achieve a smaller turning radius.



(b)
The surge protector team adaptively redesigned their product to meet the customer needs of providing transformer-sized spacing, increased stability of the base and more outlets. The casing was prototyped using a Stratasys FDM3000.



(c)
The vacuum team adapted their design to allow the product to stand upright on its own (through the addition of support feet on the rear side of the vacuum head) and parametrically redesigned (using design of experiments methods) the vacuum head to produce better suction. The prototype is shown on the right in the above photo.

Figure 3. Example products redesigned and prototyped in project 3.

At the conclusion of the theory and methodology course, students are prepared to work as members of an effective design team to gather customer needs, transform them into engineering specifications, generate product concepts, select the best concept and embody the design through state of the art manufacturing techniques. In sum, the first semester course teaches the students how to pull their discipline specific technical skills together to solve an open-ended design problem. A more detailed course description is available at: http://function.basiceng.umr.edu/idesign/method.html

Engineering Design Project: an Interdisciplinary Twist on the Traditional Capstone
The second semester course is a project course (three credit hour). With design tools and methods in hand from the first semester course, student teams complete a semester long project and produce a working prototype. The projects are externally sponsored, tied to a design competition team on campus or generated by UMR faculty. Ideally, the projects will be initiated by local industry or a government agency and the sponsor will provide a prototyping budget and technical review services. In addition to weekly lectures, student teams will work with one, or possibly several, faculty advisors who serve as technical experts for the project. These advisors will represent the appropriate departments on campus. The course is administered by the faculty of Basic Engineering.

A sample syllabus of the second semester course is shown in Fig. 4. This course begins to look more like a traditional capstone design course with the notable exception that the projects are interdisciplinary. We begin the semester by revisiting the outcome of the second project from the design methods course. Here the students spend a considerable amount of time visiting with their customer to ensure that the selected concept meets their needs. Three presentations are held where the design teams present key parts of the embodiment design process: a proof of concept of the critical component(s), a design review of the alpha (or first) prototype and a final design review/demonstration of the beta (or working) prototype. Students are assessed on individual design notebooks, team reports, presentations and peer team evaluations.

Lecture content is initially geared toward manufacturing techniques in electrical and mechanical engineering fields. External product design experts give real life "war stories" to reinforce the importance of the design methods and to describe the work environment that a product designer can expect. More advanced design theories and topics are covered toward the latter half of the semester. A more detailed course description is available at: http: //function.basiceng.umr.edu/idesign/project.html

2.2 Student Team Formation

Within BE 220/301, teams are formed to support innovative approaches to design projects. The basic premise we adhere to is to create teams with a diverse membership. One aspect of that is the interdisciplinary nature of the teams. We first make sure all teams have the appropriate technical mix (in terms of mechanical, electrical and computer engineers and engineering management disciplines). Additionally, we focus on forming teams with diverse personality backgrounds. Several studies have shown this approach to improve design team performance from both a social standpoint as well as a technical standpoint (Wilde 1997 & 1999; Neuman et al., 1999; Tett and Rothstein, 1991; Cagan et al., 2001; Magleby et al., 2000; Jensen et al., 1998). We use the Myers-Briggs Type Indicator (MBTI) to assess personality preferences.

BE 301 Engineering Design Projects - Syllabus
University of Missouri-Rolla, Winter 2002
Text: *Product Design: Techniques in Reverse Engineering and New Product Development*, K. Otto and K. Wood, Prentice Hall, 2000.
Reference Text: *Engineering Design: A Systematic Approach*, G. Pahl and W. Beitz, Springer Verlag, 1996.

Week	Date	Topic	Reading
1	Jan. 14	Original design approach review; Customer needs reassessment	Chap. 4
2	21	Concept variants (clean-up from last semester)	
3	28	Proof of concepts **Presentation to Army personnel at Ft. Wood**	
4	Feb. 4	Failure modes analysis	Chap. 12
5	11	DFM; DFA; Design for the Environment	Chap. 14-15
6	18	Prototyping techniques: mathematical models, foam board mock-ups, design drawings	Chap. 17, Handouts
7	25	Patents: search and application; Design war stories: guest speaker from GE Appliance	Handouts
8	Mar. 4	Critiquing methods; conflict resolution	
9	11	Design review of Alpha prototypes **Presentation to Army (and others) at UMR**	
10	18	Robust design	Chap. 19
11	Apr. 1	Manufacturing processes	Handout
12	8	Alternative design approach: TRIZ	Handout
13	15	Ethics in engineering	
14	22	Trust in the workplace	
15	29	Prototyping	
16	May 6	Final design presentation/demonstration of Beta prototypes **Presentation/demonstration to Army (and others) at UMR or Ft. Wood**	
17	13	Finals Week	

Figure 4. A sample syllabus for the design project course.

Used in the education context, the MBTI sheds light on a student's preferred approach to problem solving and, thus, learning (Felder and Silverman, 1998). We use the MBTI information to form teams as diverse as possible with respect to personality preferences (and consequently problem solving approach). A team formed in this manner will naturally investigate solutions to a design problem from different perspectives based upon each member's natural tendency. These differences in approaching the problem generally offer more creative solutions. Results of this approach tend to be seen through the number of concepts evaluated and the comprehensiveness of the final product.

3. Smart Marker Project

The Smart Marker Project used in the 2001-02 design course sequence has been fully funded and supported by the U.S. Army Maneuver Support Center at Ft. Leonard Wood, MO. The project is intended to lead to a more modern method for marking contaminated areas within the constraints of the existing Nuclear, Biological and Chemical (NBC) Reconnaissance System. This system allows a soldier inside a closed vehicle to safely assemble and deliver a hazard marker through a chute. The marker currently in use was designed decades ago, and consists of a simple metal base, wire mast and color-coded flags for marking. The desired marker will be "smart" in that it will provide for the transfer of data and graphics containing such information as the extent of contamination and a map of the contaminated area. The marker should also offer improved visibility in the field as compared to the old marker.

3.1 Suitability of the Project

The Smart Marker Project is particularly appropriate for our two-semester interdisciplinary design sequence for several reasons, including the nature of the deliverables, project timing, the interdisciplinary nature of the project and the proximity of the "customer." The deliverables for the project are specified as two or more different working prototypes of the new marker, so that several student teams can be provided a budget to develop their final design into a working model. The timing of the one-year project fits in particularly well with our course sequence. The final deliverables will be presented at the end of the projects course (BE301) course in May 2002. The project is inherently interdisciplinary, with significant contributions and interaction required of our mechanical, electrical and computer engineering students as well as engineering management students. A final factor that makes the Smart Marker Project well suited to our course sequence is the proximity of Fort Leonard Wood. Ft. Wood is located about 30 miles from the UMR campus, which allows the students to meet frequently with U.S. Army personnel for customer needs gathering, technical review sessions and presentation of results.

3.2 Smart Marker Activities in BE 220 and BE 301

The Smart Marker Project first appeared as Project 2 in BE 220 in the fall semester, 2001. This month-long project required that students utilize specific design methods to generate a proposal for a new product. We began by supplying the students (3 teams of 4 students each) with basic information on the Smart Marker in preparation for visiting the customer. This was followed by a trip to Ft. Wood for customer needs gathering. Personnel from the U.S. Army Maneuver Support Center gave a technical briefing, a tour of the "Fox Den" (a model of the NBC Reconnaissance System delivery vehicle) and met individually with student teams to answer questions. Photographs from this visit and from a preliminary visit in summer 2001 are shown in Fig. 5.

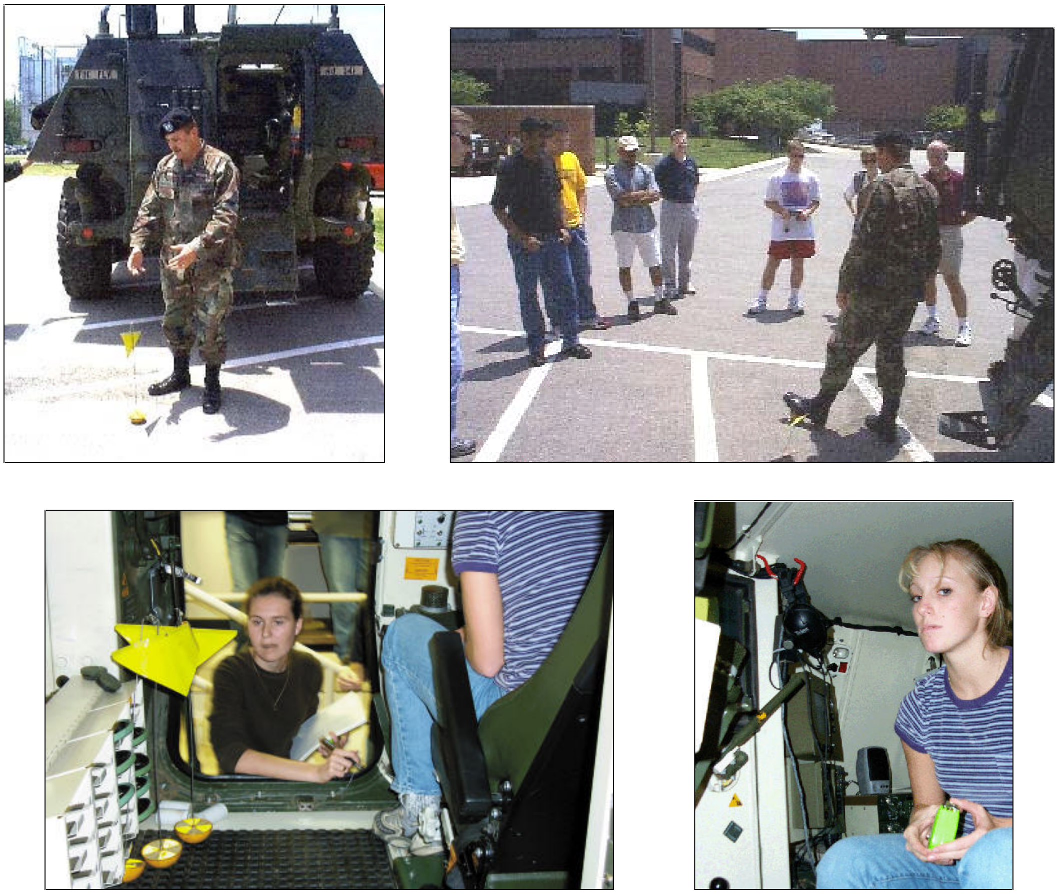


Figure 5. Site visit to Ft. Wood to gather customer needs for initial Smart Marker project work.

After gathering and analyzing customer needs, the student teams were ready to derive a functional model, complete a QFD chart, and generate concepts using the methods taught in the course. We continued our “just in time” philosophy of presenting a new method or technique in the class, and then requiring the students to apply the method to the project immediately. After generating several concept variants, the students applied screening and selection techniques to make a final selection. Interestingly, the three teams came up with quite different final designs, particularly with respect to the requirement that the mast and flag remain vertical despite rugged or sloped terrain. The designs included a balloon-based mast, a vertical stabilizer with a spring hinge and an adjustable webbed base. The student teams were required to submit a proposal detailing the results of the design methods and the final design.

The project culminated in November 2001 with presentations to Army Personnel on the UMR campus. The three teams prepared separate PowerPoint presentations describing their design methods, results and final design recommendation. Example slides from one of the presentations are shown in Fig. 6.

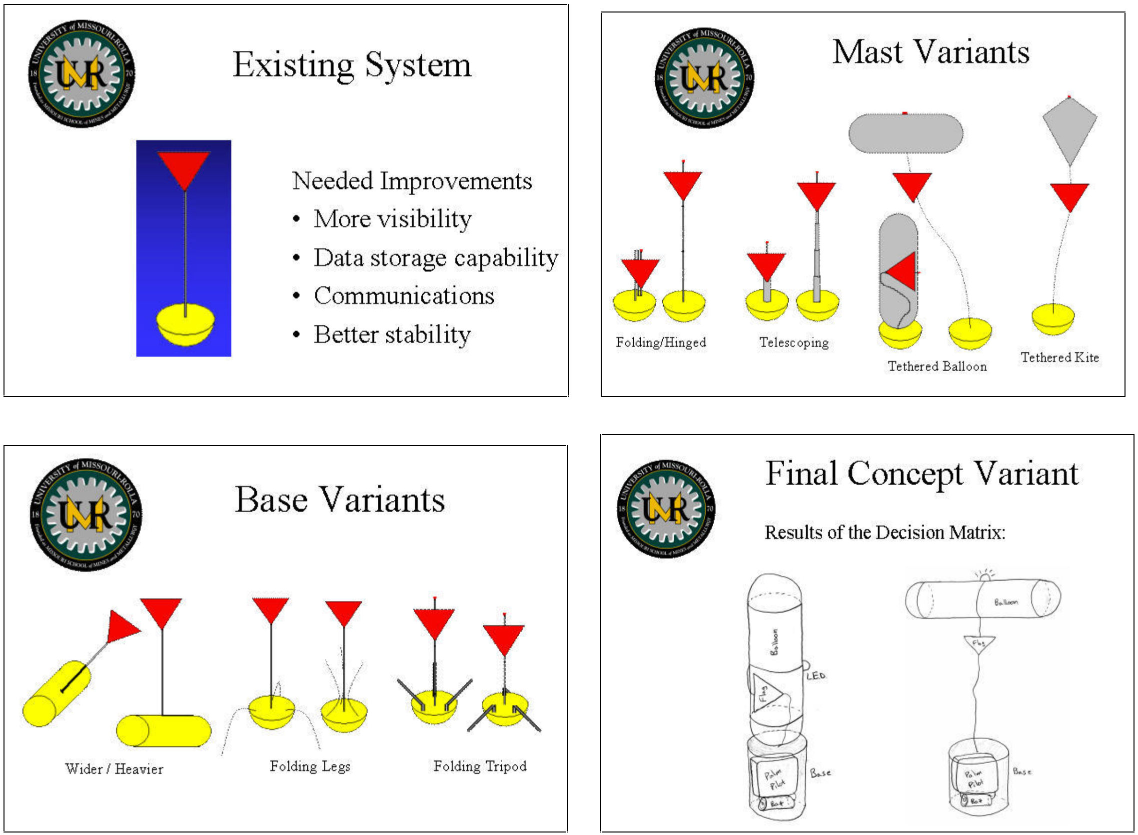


Figure 6. Example slides from Smart Marker presentation

As described previously, BE 301 is a continuation of the design methods course in that the designs developed in project 2 of BE 220 are further developed and prototyped in the spring semester. The student teams in BE 301 will complete the detail and embodiment design phases of the Smart Marker project. A mid-semester design review will be presented to U.S. Army personnel by the student teams, where proof-of-concept/alpha prototype issues will be discussed. The final prototypes will be delivered to the US Army personnel at the end of semester design presentation.

The Army personnel involved with this project have been particularly supportive of the students' efforts. We have received timely feedback after each visit, as well as ongoing suggestions for the project. After the November 2001 presentations, the Army representatives expressed some concern that the designs presented might be too complex for mass production and ease of use. Addressing this customer concern was therefore one of the first items on the agenda for BE 301. The Army representatives also requested a question and answer session with the three student teams early in the spring semester. This meeting, which took place on the UMR campus in February, resulted in some encouraging interaction and useful suggestions for the students.

Additional topics presented and utilized in BE 301 include failure mode analysis, design for the environment, prototyping techniques, robust design, manufacturing processes and ethics. The student teams have also gained experience working with a budget for their prototype. Interestingly, one of the problems encountered has been convincing the students that they can make decisions to purchase items needed. The tendency during the fall semester was to avoid spending money, even when specific inexpensive items were needed. The students have overcome this reluctance to spend money and are learning valuable lessons in budgeting.

It is expected that the BE 301 class will deliver three working prototypes to the US Army at semester's end. The Army may choose to continue with the development of one or more of the designs based on its own criteria.

4. Hurdles to Implementing an Interdisciplinary Design Curriculum

We encountered the usual challenges in setting up a new course sequence, such as attracting students, obtaining funding for a suitable project and completing the necessary paperwork to obtain approval for the courses. Our biggest challenge, however, involved convincing departments to allow our interdisciplinary design sequence to substitute for their capstone design course requirements. All engineering departments on the UMR campus meet the ABET capstone design requirement by providing a discipline-specific design course or sequence of courses. Obtaining departmental approval for substitutions of these courses is critical to the success of our efforts, since few students will take courses that do not count toward graduation.

During the first year of our interdisciplinary design sequence, we focused on attracting mechanical engineering, electrical/computer engineering and engineering management students. Through individual negotiations with these three departments, we managed to come to some level of agreement about credit for the courses. The Engineering Management Department agreed to allow our two 3-credit courses to replace two of their 3-credit requirements, where approval is on a case-by-case basis. The Electrical and Computer Engineering Department has allowed our two-course sequence BE220/301 (6 credits) to replace their two-course senior design sequence ECE391/392 (4 credits). This implies that ECE students will take (and pay for) 2 additional credits if they choose to take the interdisciplinary design sequence. Although this is not an ideal situation in terms of attracting ECE students, the agreement represents a reasonable compromise in light of the ECE requirements. In addition, the ECE department has agreed to allow BE220 to count for a 3-credit technical elective if a student chooses to just take the one course.

The Mechanical Engineering department agreed to allow BE220 to count for a 3-credit technical elective, but decided not to allow substitutions for their senior design course, ME261. This means that an ME student who wishes to pursue an interdisciplinary design project by taking BE220/BE301 will not receive credit toward graduation for BE301. This implies, of course, that few ME students will choose to take BE301. Since ME students comprise a significant percentage of students who might be interested in an interdisciplinary project, this situation causes us some concern (we did retain all except for one of our ME students from BE220 in the BE301 course, they are taking it as an extra course). However, the UMR campus offers a total of 13 engineering majors, so there is plenty of opportunity to work with additional departments and attract a diverse group of students to our interdisciplinary senior design sequence.

Another potential concern is the resource requirement for design courses that are heavy on hands-on projects. We approach this by using small scale consumer products (costing less than

$50) for the reverse engineering projects in the first semester course. With teams of four or five students, we believe that this is a manageable financial situation. The novel product development in the second semester does require a more significant commitment of resources. We were fortunate to have a source of projects and funding by the US Army at Ft. Leonard Wood. In the future we will have to seek external funding to continue the projects at the desired level in the second semester course.

5. Conclusions

The interdisciplinary design curriculum offered by BE 220/301 pushes design education to more accurately reflect current engineering design practice in today's technological workplace. Over the history of engineering, the engineering education pendulum has swung between the extremes of a vocational, apprentice-like education and a strict, theory-based engineering science approach. The design curriculum proposed here is our attempt to strike an appropriate balance between engineering science and the ability to produce physical artifacts.

The key benefit of our interdisciplinary design course is the emphasis on design theories and methodologies that allow students to learn how to design by following a structured approach. Simultaneously, we integrate hands-on experiences throughout the courses to allow the students to actively experiment with the new design methods immediately. This approach offers students an advantage in today's engineering workplace. In addition to possessing outstanding technical skills, students with an interdisciplinary design background will be able to make an immediate impact in product design team situations.

Acknowledgments

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