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Multidisciplinary Capstone Design at the University of Houston

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ABSTRACT

In this paper we identify some of the issues and problems that we confronted while developing a new, one-semester, interdepartmental, multidisciplinary capstone design course. We implemented the following changes to the pre-existing capstone design course:

- **utilized a website to enhance information transfer,**
- **modularized the course and replaced lecturing with facilitating,**
- **introduced a studio/critique teaching format,**
- **integrated communications professionals into the teaching of the course, and**
- **allowed the students to be involved in establishing the final expectations for their project.**

The details of the implementation process, the effects of the changes, and the students' responses are discussed. Examples of some of the projects are given.

Keywords: capstone, design, multidisciplinary

I. INTRODUCTION

Capstone experiences are common in many disciplines and provide students with the opportunity to demonstrate that they can integrate their discipline specific knowledge with more general problem solving skills. Of course, such experiences are essentially required as part of engineering and technology programs in the United States. Most (about 80% [1]) engineering programs require a team experience, with 40% [1] of those offering the possibility of interdepartmental teams. Approximately half the capstone experiences extend beyond one semester or quarter [1]. A Bibliography of multidisciplinary courses and projects is at the end of this paper.

Until 1980 the capstone course in the Department of Mechanical Engineering (ME) at the University of Houston (UH) had little structure or content beyond that needed to complete the largely faculty provided projects. In 1980 the mechanical engineering capstone course was reorganized. Industry began to provide and sponsor projects. Student teams were set at four and informally "bid" on the projects. Course content began to evolve. Design methodology and optimization were the first main topics. In 1985 the Industrial Engineering (IE) capstone course was combined with the ME capstone course forming the first multi-disciplinary capstone course in the College. The content of the combined course continued to evolve. In the late 1980s and early 1990s statistics, project planning, and some instruction in technical communication were added.

The course had always been a one-semester, 3-hour credit course that was offered every fall and every spring on an alternating day-night schedule by a single instructor. About 70% of the projects were provided and sponsored by local industry, and a majority of them, at least since 1991, were related to the petrochemical industry. The remainder of the projects were provided and sometimes sponsored by faculty. In addition to the client-provided "engineer-in-charge," each team was assigned a faculty advisor. Short, weekly progress reports and formal written and oral final reports were required from each team. By the mid-1990s the course also had considerable content, e.g., the design process, oral and written technical communications, project planning, risk analysis, ISO 9000, engineering ethics, statistics, optimization, and present value analysis.

In 1998 the Department of Electrical and Computer Engineering (ECE) began requiring the completion of a common capstone design course as part of its BSEE and BSCE (computer engineering) degrees. Through mutual agreement this course met with the existing IE/ME capstone course. Hence all the students from the four programs (Computer, Electrical, Industrial and Mechanical Engineering) were required to take the same capstone course. There was a three-year transition to the full implementation of new multidisciplinary capstone course. In a previous paper [2] the following capstone course issues confronting the instructors were presented:

II. CAPSTONE ISSUES

A. Problems Associated with the Transition to the New Environment

Enrollment: The IE/ME course enrollment in the mid 1990s was between 30 and 40 students each semester. It was clear that changes would be necessary as the College granted more than 100 BSEE and BSCE degrees annually in 2000.

Team Teaching: A plan for the division of labor was needed.

Multidisciplinary Teams: Previously there were no restrictions on the make up of the teams. The guidelines for the combined course required that at least two disciplines be represented on each team.

Multidisciplinary Projects: As noted, the projects in the IE/ME course had been primarily from the petrochemical industry which was appropriate for a primarily mechanical engineering course in Houston. However, with the new course, enrollment was expected to be primarily electrical and computer engineering students and a larger variety of projects would be required.

B. Problems Associated with Team-Oriented Design Courses In General

Individual Grades: One of the objectives of the course is to teach students to become "team" oriented and to accept both the responsibility and rewards of team membership. However, grades are assigned to individuals in an academic environment. As an alternative to simply assigning to individuals the grades earned by their teams, we desired to introduce a measure of individual accountability into the grading process.

Class Participation: Students tend to become preoccupied with their own projects and pay little or no attention to the other projects. We felt students would benefit from some involvement with the other projects.

Analysis-Based Design Content: The ultimate product of any design process (regardless of the discipline) is an artifact (using the broadest possible definition) that satisfies the constraints and aspirations of the client. One of the aspects of engineering design that sets it apart from design in many other disciplines is analysis. We wanted to assure that our designs were based on good engineering analysis and produced a satisfactory artifact.

Realistic Design Constraints: Although the expectation is that students will be prepared for the capstone experience through exposure to engineering standards and realistic constraints throughout the curriculum, these issues must also be addressed in the capstone course. With teams of students working independently on different projects there appeared to be little opportunity to address these issues except on a team by team basis which seemed very inefficient.

Demonstration of a Successful Design: Validation of the product of the design is an important part of the design process. We prefer projects that result in an artifact that can be tested (validated). The question is what to do about artifacts that fail their "test", about teams that fail to produce a testable artifact and about projects that, by definition, will not produce an "artifact."

Project Completion: A team's inability to satisfactorily complete its project is a frequent problem in general and even more critical in a one-semester, last semester, design course. We wanted to develop a process that would make it more likely that projects would be satisfactorily completed on time.

Meaningful Instruction and Feedback in Communications: We were concerned about the generally poor quality of communication skills exhibited by some students in both their presentations and reports. The large class size prevented individualized instruction that many students needed and, as engineering faculty, we were really not prepared to turn this design class into a communications class.

Uniformity of Grading: In a large design class it is impractical for one person to be responsible for grading all the written assignments or all the oral presentations. Also, there is a subjective element to grading written and oral reports and the artifacts of design. How could we be assured that the grading would be fair and uniform?

Class Communication: Communications in a large class with numerous reporting and demonstrating requirements, with numerous scheduling issues, with numerous projects, with potential team dysfunction, etc. would be difficult.

Client Consistency: An industrial client's objective is seldom the same as the instructor's; so there is usually a little give and take before the project description is accepted. As the project proceeds, new ideas evolve; old ideas are shown to be unacceptable or unworkable; and there is a tendency on the part of the client to modify the project. How are the issues associated with a changing set of constraints and goals handled in light of the course requirements, e.g., finish on time, maintain uniform expectations, produce an artifact, validate results, etc?

Quality of Client Consulting: Despite the client's good intentions, many issues affecting his availability and interest may be beyond his control. A common problem is a client's failure to provide promised information, materials, equipment or access in a timely manner, if at all. The student team can not be held responsible for the client's failure to deliver, but neither is it fair to give the team a "free ride" for its project.

Quality of Faculty Advising: The students' ability to access a busy faculty member and the faculty member's interest in carrying out his advising assignment are variable.

III. RESPONSES TO THESE PROBLEMS

Four changes from the preexisting IE/ME capstone design course were made in the course that addressed most of the issues raised above. These changes were:

- to modularize the class by dividing it into small groups of students (cohorts) and changing the instructor's role from one of "lecturing" to one of "facilitating";
- to integrate the resources of the newly established UH Writing Center into the teaching and evaluating of communications for the course;
- to utilize a studio/critique teaching format, adapted from the visual arts; and
- to replace many of the industrial projects with projects from the College's research laboratories.

These four changes are discussed in more detail below.

A. Modularization and the Facilitators

Dividing the class into small groups of teams or cohorts developed as a natural consequence of the instructors' decision to reduce the course "content" and focus on a more "hands-on" approach to managing and encouraging the multidisciplinary teams. The "lecture" material was "repackaged" and presented in interactive, cohort meetings. The project teams were grouped into cohorts of four teams or less (16 or less students). In the spring 2004 there were 88 students in the class so each of the three facilitators (a.k.a. the three instructors) had responsibility for two cohorts of three or four teams each. Each cohort had eight, 90-minute, meetings (More information is given below and in [3] on how these cohort meetings were conducted in a studio/critique format.) with its facilitator. Three cohorts met together on a rotating basis for the student oral presentations. Each team participated in four presentation sessions. Its representative gave his/her presentation, and the team listened to ten to twelve other presentations. Hence everyone heard at least one presentation from each of the other teams at some point in the semester. The entire class met together only during the first week. A website (utilizing Blackboard®) was initiated and served as the central contact point for the class. All students and facilitators could contact each other by email through the website. All assignments, discussion materials, grading rubrics (See next section.) were posted on the website. In addition to the hardcopy submissions, copies of all student work (including PowerPoint slides) were submitted to the website.

B. Writing in the Discipline Program

In 2000 the UH Writing Center was established to provide a campus-wide resource to assist students in their writing. In 2002 a special Writing Center program, Writing in the Discipline, (WID) was initiated. The WID program sought opportunities to actively (by working with the instructors) intervene in courses across the campus in which communications skills were stressed. The rationale for the intervention was that general composition courses cannot adequately prepare students for discipline-specific writing. (More information on the UH Writing Center, its WID Program, and its interaction with the capstone course can be found in [4].) For the capstone course this intervention produced several significant results. With the assistance of the WID program a comprehensive set of individual and team communication projects was established. Each team member was personally responsible for the one oral and one (different) written report. These reports could be a proposal, a progress report or a technical report. These two reports represented 15% of the individual's course grade. Five, team-prepared, written Planning Reports were required and reviewed in the cohort meetings. The team was also responsible for a final technical report, a final oral presentation, a poster and an extended abstract. To provide assistance to the students in preparing these documents and presentations, just-in time (JIT) interactive workshops were developed and conducted by Writing

Center personnel. The grading criteria (These rubrics were developed jointly with the WID program.) for these assignments were available for each type of report, were posted on the website, and were discussed in the workshops. Each team prepared a poster for its project that was displayed in the engineering building commons for three days and presented a 30-minute oral report on the last Saturday of the semester. These presentations were part of an all day affair and lunch was served. All students intending to take the capstone course in the next semester were required to review (and evaluate) the posters and attend (and evaluate) at least three presentations. During the last week of the semester each team scheduled a one-hour “out of class” meeting with the facilitators to present and defend (validate) its project (artifact).

C. Adaptation of the Studio/Critique Teaching Format

Introduction: The use of a studio environment in the teaching of engineering design is briefly discussed in [5], and experiences in using the critique in a studio environment for the teaching of introductory engineering design are presented in [6]. The critique and the studio environment have been an important teaching tool in the visual arts for much of the last century. In the visual arts, class size is limited to about twenty students, and the object of the design process is being created in the studio under the watchful eye of the instructor. Neither of these conditions was satisfied in our capstone design course. As many as ninety students were enrolled, and the available meeting room provided no work area or storage facilities. Another issue that could interfere with the successful implementation of the studio/critique environment was the difference between the “supportive culture” that normally exists in a visual arts class and the “competitive culture” that many times exists in engineering classes. In spite of these differences and apparent obstacles, we developed a very effective technique for improving the design experience for our students through the use of a modified studio/critique process. This technique required the “modularization” process (forming the cohorts) discussed above so the technique can be contracted or expanded to accommodate (in theory) any number of students (with the appropriate number of cohorts). The following sections of this paper will provide a brief description of the how these processes were integrated into the course and how the resulting experiences and interactions improved the quality of the final product, team work, and communications. The studio concept and the culture of the critique are explained in detail in [2]. Only a brief review is given here.

The Studio and the Critique: The studio is equivalent, but definitely not the same as, the engineering or science laboratory. In the studio paradigm, projects are assigned to or developed by the individual students, and it is assumed that the student will devote a certain amount of time, including time in the studio, to completing the project. It is the critique and the culture of the critique that more than anything sets design education in the visual arts apart from engineering design education. Two or three critiques are usually associated with a given project, so the timing of the critiques is related to the timing of the project. The idea of seeking help from peers and teachers is not new to engineering students. However, what is new is the sharing of ideas and the unsolicited advice. An important aspect of the studio culture is that the student and the instructor work as a team. The studio requires two resources that have equivalents in engineering education: the meeting space or studio (the laboratory for engineering) and the human resource (the instructor for both). The important elements of the studio are that the size of the classes is limited and the completed works of previous classes and other drawings, posters, and artifacts related to the discipline are on "permanent" display. Access to the studio is granted at any time during the class day to any student enrolled in a class using that studio. It is not uncommon to see students of different classes (and academic levels) working side by side in the studio during a class that neither is enrolled in and to see students working alone in the studio when classes are not meeting. The instructor's office is usually adjacent to the studio, and the instructor is usually accessible throughout the day. This picture may resemble the "open lab" concept used in the some engineering programs and in fact it is similar in appearance (except for the electronics and the hardware). The major difference is that in the engineering laboratory there is usually a specific outcome objective, a data collection process and a reporting requirement. In the artist's studio, the objective is usually not as well defined as in the engineering sense. The expected result is a new and unique image or artifact that satisfies to varying degrees an array of preset constraints and goals that are generally based on a "sensing" or "feeling" rather than on demonstrating or illustrating an engineering principle. The instructor's role is also quite different. In the engineering laboratory course the instructor is attempting to help the student find the "right" path; in the studio, the objective is for the student to discover his/her own path.

The Culture of the Critique: As noted above the educational process in the visual arts is more of a team process: the student and the teacher being the team, than it is in engineering education. Of course, in a larger project there could be a "team" of students. In another sense all the students in the art class view themselves as "team members", or at least consultants, on all the projects in the class. Once this "team" culture is accepted, the role of the instructor is much easier. Criticism is viewed positively and constructively. Students welcome the instructor's comments. Over the years of experiencing "artistic" criticism (i.e., sometimes vague opinions and multiple suggestions as opposed to declarations that the work is either right or wrong, along with specific suggestions, rules, or references), the visual art students learn to accept and even relish it because they trust the instructor and acknowledge the "team" aspect of their relationship. It is true that the instructor must eventually "judge" the student, but that judgment is based on more than simply the student's artifact or his/her performance on a few "tests"; it is based on a semester long "working relationship".

Adapting the Studio/Critique Teaching Model to Capstone Design: We decided to use the studio/critique teaching model in the hope that we would be able:

- to achieve a better team effort and final product,
- to increase each team's effectiveness by providing more timely intervention,
- to encourage more discussion of the projects within the teams and among the teams,
- to provide many opportunities for each team member to informally discuss, explain and/or defend his/her project and the design decisions,
- to allow peer questions and challenges,
- to provide an environment for more effective interaction between the facilitators and the students with the specific purpose of improving the planning and communication skills of the students,
- to establish a non-competitive environment in which all teams could benefit from the collective input of peers and facilitators, and
- to discuss (rather than lecture about) a series of design, planning, ABET, and communications topics.

There were eight meetings with the teams in their cohorts. Before each meeting the teams were told (through the website) of the assignment for that meeting, e.g., discuss the team's Gantt Chart, state the team's three most important milestones, be prepared to discuss the impact on their design on the three most important constraints listed in ABET Criterion 4 (now part of ABET Criterion 3c), define the final product of the semester and how the team plans to demonstrate that it is successful (and what is success?), etc. If the team's discussions were not satisfactory, they were told to prepare a written reply to the facilitator. During one team's discussion, questions were posed to the other teams present. Teams were always told to bring any artifact (component, subassembly, etc.) if one were available. Several teams will inevitably have common design issues, e.g., fabrication of printed circuit boards, and all teams can benefit from another team's experience.

D. Use of the College of Engineering's Research Laboratories for Projects

There is a strong feeling by many who teach capstone design that industry should be the source for as many capstone design projects as possible. Under certain circumstances we could agree. However, our view is that in general industry is not able to provide the consistency in objectives and quality of consulting to assure a satisfactory result. Some would argue that "that's life" and the students will have to get use to it. Our feeling is that we are responsible for providing a realistic and "fair" experience that will be evaluated on its merits. Attempting to account for incomplete (company) information, denied access, late or no promised materials, a change in goals, etc. lead to inconsistency in grading. Too many industrial partners take the approach that "everyone worked hard and did a good job" no matter how unsuccessful the project is. As noted above we still accept industrial projects, but a good number of our projects now come from our research laboratories and from us. The appendix presents a list of projects for 2003 and provides additional information on two of them. Reference [7] provides more details on these projects. In using projects from the College's Research Laboratories, we are careful to make sure that these are actually "design projects" usually requiring the design, construction and testing of an artifact and not "research projects" limited to information gathering and analysis.

IV. SHORT-TERM RESULTS

A. Cohorts and Facilitators

Splitting up the class and eliminating the formal lecturing by itself would not necessarily represent any improvements. However, without this first step, the rest of changes described here would not have been possible.

B. Collaboration with the Writing in the Discipline Program

We observed a definite improvement in the quality of the writing and the presentations in just one semester. Part of that improvement was probably due to that fact that we have done a better job telling the students what we want. Reference [4] discusses more of this collaboration and presents the results of a student survey which is summarized here. Students used a Likert Scale (5 = strongly agree,..., 1 = strongly disagree) to respond to a series of statements. About 75% agreed or strongly agreed that their skill level in technical communications had increased while only 10% disagreed. For four of the six workshops surveyed, there was over a 70% "approval rate", e.g., at least 70% of the responses agreed or strongly agreed that they were helpful. There was only a marginal increase in the students' "before" and "after" self-assessment of their ability to express themselves clearly. Although the number of students who disagreed or strongly disagreed that they were able to express themselves clearly through writing or speaking decreased from 25% to 7%.

C. Studio-Critique Teaching Format

Generally all our intents (above) were satisfied, and several additional benefits have also been realized such as (These benefits are briefly discussed in detail below. More discussion can be found in [3]):

- An opportunity to review and correct common misconceptions and mistakes based on "live case studies", i.e., the ongoing projects;

- An opportunity to link the planning activities with the development of effective communications;
- An increased emphasis on demonstrated progress; and
- A positive student reception to this process and genuine synergism among the teams.

Live Case Studies: Case studies are commonly used in engineering education to demonstrate best practice scenarios by describing the set of facts and decisions related to the systematic solutions for given problems. Normally "successful" solutions are provided although one can imagine that the discussion of suboptimal solutions in which alternatives are presented would also be effective. Problem solving is a process that can be learned. However, the process can be abstract and unrealistic when presented "out of context." In the studio environment each team discusses its "real" problem solving process and difficulties. Other teams can relate to the experiences of their peer teams because they are probably experiencing similar issues.

Planning and Writing: Many teams have difficulty in organizing and planning both their projects and then their writing about the projects. We note that two topics often included in capstone design courses are project planning and technical communications. We have found that these two topics are so closely linked that we are able to address both together, sort of "killing two birds with one stone." (See [8] for more details.)

Demonstrated Progress: In the past we had experienced serious disconnects between reality and what many teams state about their progress in our conversations and in their progress reports. Part of this problem is an honest underestimate of the effort remaining to complete and debug a software program or to fabricate and test a prototype. Sometimes, unfortunately, it appears to be an attempt to deliberately mislead or misinform the facilitators. Requiring that artifacts of the design process be brought to the studio has essentially eliminated this problem.

Synergism among the Teams: As noted above, the teams have demonstrated a genuine interest in helping each other. Not only is class morale higher, but the project results have improved. By allowing the teams to "look over each others' shoulders" the less effective or less motivated teams aspire to work harder. The more successful teams tend to work harder as they see others begin to work up to their level. It is a "win-win" situation.

D. From the Students' Point of View

At the end of the Fall 2003 and Spring 2004 semesters the students (128 total) were asked to complete a survey that asked them to rate their level of agreement with statements related to various aspects of the course using the same Likert scale described above. (See [2] for details.) Their responses are presented in Table 1. The last five statements relate directly to the changes in the course discussed in this paper. Statements 15 through 19 have to do with the reorganization of the course into cohorts. These responses are generally "positive" and even the responses to #16 and

	statement	5[2]	4[2]	3[2]	2[2]	1[2]	N[1]	avg
1	I was looking forward to taking this course.	48	50	25	4	1	128	**4.09**
2	The course was more work than I thought it would be.	44	36	39	15	3	128	**3.80**
3	I am proud of my effort in this course.	79	36	10	1		128	**4.52**
4	I am proud of my team's effort in this course.	62	47	11	5	3	128	**4.25**
5	I am proud of the "solution" that my team produced.	57	54	13	3	1	128	**4.27**
6	The facilitator was helpful and interested in the project.	54	48	18	4	3	127	**4.15**
7	The faculty advisor was helpful and interested in the project.	52	43	25	5	3	128	**4.06**
8	The Planning Reports were helpful.	27	31	33	26	11	128	**3.29**
9	My team had the necessary information, materials and personnel.	44	47	21	11	5	128	**3.89**
10	I like the fact that there was a peer evaluation of team members.	62	40	23	1	1	127	**4.27**
11	My team work skills have improved by taking this course.	50	52	23	2	1	128	**4.16**
12	My public speaking skills have improved by taking this course.	51	49	20	5		126	**4.17**
13	My planning and time management skills have improved by taking this course.	44	46	31	4		125	**4.04**
14	My technical writing skills had improved by taking this course. (spring 2004 only)	31	38	14	4		87	**4.10**
15	The cohort environment was an effective compromise between team meetings and class meetings for discussions.	49	58	17	2	2	128	**4.17**
16	The interactions with the other teams during the cohort meetings were helpful.	40	54	21	9	4	128	**3.91**
17	I like the fact that I was able to learn about all the projects.	51	53	20	2	1	127	**4.19**
18	My team received useful help by interacting with other teams.	28	47	40	10	3	128	**3.68**
19	I liked the fact that we were responsible for demonstrating that our "solution" worked.	59	49	18	2		128	**4.29**

[1] not all students responded to all the statements
[2]Likert scale: 5= strongly agree; 4=agree; 3=neutral; 2=disagree; 1=strongly disagree

Table 1: Student Survey Reponses for Fall 2003 and Spring 2004 Semesters The last five statements relate directly to the structural changes in the course. Statements 12 through 14 related to the interaction with the UH Writing Center.

#18 which are a little less positive indicate that about two-thirds of the students indicated that they were helped by the interactions with other teams. The strong positive response to #19 is somewhat surprising but illustrates the strong identification the students have with their project; that is, they want to see it work.

V. MID-TERM RESULTS
(WHAT WE LEARNED ABOUT THE CAPSTONE ISSUES)

The resolution and status after two-years (2005) to the Capstone Issues defined at the beginning of the paper are now presented.

Enrollment: The cohorts and the website solved this potential problem. The instructors formed and divided up the cohorts and coordinated their joint meetings for the presentations.

Team Teaching: The three instructors worked well together and were able to resolve all issues.

Multidisciplinary Teams: Under ideal circumstances combining students with different technical backgrounds seemed like a good idea. In practice, it "sort of worked out", but there were still situations in which it did not "work out" satisfactorily, for example when there were IEs or EEs on a team with a finite element stress analysis project, or MEs and EEs on a team with a factory layout project or IEs and MEs on a team with an autonomous robot with no structural issues project. The major problem has been that it is difficult to match the technical requirements for a finite number of projects to the technical makeup of a particular team. More precisely, we had difficulty finding true multi-disciplinary projects. This problem was especially true of the projects from industry, and when we attempted to redefine the projects to include some additional issues, the industry representatives were not too happy for the most part. Even in these "unbalanced" teams there was still the possibility of a benefit, for example, for the IE who learned about finite element analysis. Unfortunately, this scenario was the exception. The usual scenario was that the IE did nothing but write the report.

Multidisciplinary Projects: As noted above, these projects are difficult to develop. Of course, the instructor could make them up. And, yes, many teams could work on the same project, but this approach would take the realism and variety out of the course. It would become a "make work" situation.

Individual Grades: Thirty percent of the grade was based on individual work: a written (10%) and oral (5%) report for the team and the Final Exam (15%). A peer evaluation was used to determine the individual credit for the team grade; about 10% suffered a grade reduction.

Class Participation: The cohorts and the presentations have worked well in this regard. About two-thirds of the Final Exam was over the "other" projects.

Analysis-Based Design Content: To the extent possible analysis was required before construction could begin.

Realistic Design Constraints: The cohorts have provided a good opportunity to discuss these issues even though a single project rarely involves very many. However, when four projects were grouped there was usually sufficient opportunity to discuss most of these issues. Even if the discussion wandered from the specific projects, the cohort was small enough that a meaningful discussion was still possible.

Demonstration of a Successful Design: Validation was probably the most important innovation in the course. Teams were required at the beginning of their projects to state their expected outcomes and how these outcomes would be demonstrated, e.g., an autonomous device weighing less that three pounds that would traverse the maze, pick up the cube and return within ten seconds. As the semester progressed, teams were allowed to change their expected outcomes with justification and the approval of the instructor. About two weeks before the end of the semester, the expected outcomes became fixed. Teams schedule a 60-minute meeting during the last week of the semester with the instructor and one or two other faculty to demonstrate their devices. These faculty, together with the project adviser and the client, determine a grade together (for about 30% of the total project grade).

Project Completion: Completion went hand in hand with the Demonstration of a Successful Design. The object was to have a realistic goal which was usually difficult to specify at the beginning of the semester. By allowing the goal (or outcome) to shift, e.g., based on availability of parts, students have a realistic, but not trivial, goal. This exercise helped the students to develop more realistic planning skills, while at the same time allowed them to "finish the project" and not just "end it"

Meaningful Instruction and Feedback in Communications: With the help and cooperation of the UH Writing Center, as described above, improved communication skills was one the great success stories of the capstone course. This collaboration has lead to a new technical communications course initially taught by the UH Writing Center personnel and sponsored by the College Engineering. It is now taught in the College and coordinated by the College's new Director of Technical Communications across the Curriculum and intervention has been established into several other classes in the College. [9–11]

Uniformity of Grading: This issue turned out not to be a problem. The oral reports, the posters, and the validations were team graded. All written reports produced within a given cohort were graded by instructor responsible for that cohort.

Class Communication: The website took care of this issue.

Client Consistency: This issue remains unresolved.

Quality of Client Consulting: We continue to have problems here as well, and it is not just with the outside clients. Undergraduates sometimes have difficulty finding their faculty clients. On the other hand some faculty take this responsibility very seriously and treat the project as a thesis and expect too much. This problem was particularly obvious when we saw the large disparity in the quality or completeness of similar projects for different clients.

Quality of Faculty Advising: See the comments on client consulting.

VI. LONG-TERM RESULTS

Effective for the Fall 2005 the three-department, multi-disciplinary capstone course was discontinued. The IE/ME capstone course was reinstituted, and a separate CE/EE capstone course was established. This decision was based on a mutual agreement among the departments. There were some disagreements over the allocations of resources, but in the final analysis the class was just too large. The good news is that both of the capstone courses are currently organized and run as their three-department predecessor capstone course was. The opportunity exists for students to work on teams shared between the two classes, but few do. There is a common poster day for the two classes. For the fall 2009, the IE and ME Departments will begin to offer their own capstone courses and in the fall 2010 the ME course will be taught over two semesters.

VII. CONCLUSIONS

This paper has presented a series of issues and their resolutions associated with the development and implementation of a one-semester, multidisciplinary capstone design course involving the seniors from four engineering programs. Additional issues associated with team-oriented design classes in general were also addressed. The significant beneficial changes that were introduced into the new course in 2002 and which continue to be used today are:

- using a web site to enhance information transfer;
- using cohorts to modularize the large number of students and teams;
- using a "studio/critique" teaching environment
  - to provide a less threatening environment which allows students to informally discuss their projects,
  - to encourage teams to discuss common areas of concern with other teams, and
  - to provide the opportunity for teams to become acquainted with the other projects;
- involving a group of professional communicators (initially involving the staff of the UH Writing Center but now the College of Engineering's Technical Communications across the Curriculum Program) in the teaching and evaluating of the oral and written reports; and
- allowing the students to become involved in establishing the expectations for the artifacts of their design process such that the project validation is much more likely to occur successfully.

Two issues that remain to be addressed are

- reducing the variability in client support and technical advisement and
- matching the skill set required for the project to that of the team.

As noted, the students have reacted positively to these changes. Perhaps the most noteworthy success is that nearly all projects have been "completed" satisfactorily, even if some are completed with a reduced set of requirements.

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AUTHORS

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Paul Ruchhoeft is an associate professor in the Department of Electrical and Computer Engineering. His research interests are in the areas of nanolithography and nanofabrication. He began teaching the capstone design course in 2001.

APPENDIX

In 2003 (spring and fall semester combined), there were 140 students formed into 36 teams working on 26 different projects divided among the three instructors. The projects are listed in Tables A1 and A2. Short descriptions are included for the projects from the University's Research Laboratories (Table A1).

Two projects, completed in the spring 2003, are described in some detail. These projects were proposed and funded by the Smart Materials and Structure Laboratory in the Department of Mechanical Engineering. These projects have been singled out because they are good examples for having students face and solve a variety of engineering design problems from several disciplines and for providing "hands on" access for all engineering students in the program to elements of two emerging technologies in the controls area. The teams were given similar instructions for both projects: Develop interactive, hands-on experiments to illustrate the features of 1) a magneto-rheological (MR) fluid and 2) a shape memory alloy (SMA).

TWO PROJECTS

A magneto-rheological (MR) fluid is a liquid whose viscosity changes proportionally with the strength of an applied magnetic field. When the magnetic field is controlled by a computer, an MR fluid system can also become a very effective control device. Shape Memory Alloys (SMAs) are "smart" materials that have the ability to return to a predetermined shape when heated or cooled. This property enables a SMA to be used as a sensor or actuator and is becoming a popular choice for many modern controls applications. Both of these materials, SMAs and MR fluids, are relative new control devices and not normally prominent in the core undergraduate curriculum, although they are normally covered in elective controls courses. With the intent both to provide meaningful electro-mechanical system design problems for the capstone class and to raise the awareness and interest in these materials for students at and visitors to the University of Houston, the development, design and fabrication of the demonstration projects were assigned to the two design teams. One team was composed of two Electrical and Computer Engineering (ECE) students and two Mechanical Engineering (ME) students; the other, of one ECE student and three ME students. Three demonstration/experiments were developed using a hydrocarbon-based MR fluid (MRF-132AD): a disk brake, a vibration damper and a crane. Two sets of demonstration/experiments were developed and implemented using a nickel-titanium alloy (Nitinol) as the SMA: a lifting device and a flexible limb mechanism. Both sets of demonstrations were housed in ventilated, acrylic cases that are now displayed in the lobby of the Department of Mechanical Engineering.

Design of In-Vaccum Cold Sink

A backside helium cooling system was designed to reduce stencil mask distortion due to overheating during x-ray lithography used for integrated circuit fabrication. Thermistors, placed on the membrane surface, were used to measure the temperature of the fragile membranes. The thermistors were calibrated with the aid of a digital hot-plate.

Manufacturing Research Data Base

A user-interface to an existing database was developed using MS Access database software and ColdFusion web-application software to establish a more efficient method for tracking the data associated with the manufacturing of films and masks from silicon wafers. The final product was a thoroughly tested, web-based system in which the user has the ability to scan a bar code and retrieve or input data associated with a wafer's manufacturing process. A comprehensive user's guide was provided. (2 projects)

A "Feeling" Robotic Hand

This was a haptic feedback, demonstration project, and represented the first step in the design and implementation of a "Feeling" Robotic Hand that could be used, along with other sensors, to practice medicine at the distance. A pressure sensor (acting as a "probing finger") was calibrated and used to produce a proportional current to drive a force actuator, a voice coil, that applied a calibrated force to the "sensing finger".

Demonstration of a Magneto-Rheological Fluid

Three interactive experiments/displays illustrating the properties and applications of a Magneto-Rheological (MR) Fluid were designed, fabricated and tested. An MR fluid is a fluid whose viscosity changes in the presence of a magnetic field. The three experiments were: a MR fluid disk brake, a vibrating platform with MR fluid dampers, and a crane that raises and lowers an electromagnet in and out of an MR fluid. All three experiments possess interactive controls and were mounted in a ventilated, acrylic display case.

Demonstration of a Shape Memory Alloy

Two electrically controlled, interactive Shape Memory Alloy (SMA) actuator demonstrations were designed, fabricated and tested. A SMA is a metal that demonstrates the ability to return to some previously defined shape or size when subjected to the appropriate heating or cooling. The first demonstration is a weight lifting mechanism that uses Nitinol wire to lift twenty pounds when the wires are electrically heated. The other demonstration is a flexible limb mechanism composed of a strip of flexible metal that has Nitinol wire actuators attached to both faces of the limb. The coordinated, alternating electrical heating of each wire allows controlled movement of the flexible limb. Both demonstrations are housed in a ventilated acrylic case currently on display in the lobby of the Department of Mechanical Engineering.

Implementation of a Positional Feedback System for Metrology Tool

The x-y stage of a metrology tool used to examine semiconductor wafers was upgraded by implementing a positional feedback system using a proportional-derivative control scheme and coded with LabView software that interacts with a charge-coupled-device camera to determine the coordinates of the stage. Testing of the system revealed that the system's precision was about 20 microns which was not acceptable. Part of the problem was traced to way the camera acquired images and to the positioning errors associated with the DC motors.

Remote Sensing Hand Using the Internet for a Haptic Interface

The "Feeling Hand" project from the previous spring was repeated. Different techniques were utilized for both the "probing" and the "sensing" finger, and an internet link was added between the probing and sensing functions. A unique "probing finger" sensor was designed fabricated, calibrated, and tested successfully. The internet link was established using LabView. An attempt was made to develop a novel "sensing finger" using a (variable viscosity) MR fluid (see above) as the working fluid in a cylinder-orifice system but it was not successful due to the clogging of the orifice.

Smart Crutch Using an Electro-Magneto Fluid

A Magneto-Rheological (MR) Fluid (see above) sponge damper controlled by an electromagnet was used in the design of an innovative crutch. A predetermined (and controllable by the user) electrical signal was generated with each crutch impact with the ground and then used to control the "damping" constant of the system (through the MR fluid) to reduce the impact shock of the crutch. The design was fabricated but met with only limited success because a damper system with a satisfactory orifice opening was not found. The iron particles present in the MR fluid tended to plug the orifice.

Active Guide Wire for Angioplasty

A method was developed and implemented (in principle, not in patients) to overcome the lack of control in current procedures for directing the guide wire into position in the artery for an angioplasty procedure (displacement of plaque buildup in coronary arteries). Two Shape Memory Alloy (SMA, see above) actuators were micro-welded to opposite sides of the wire. By selectively heating and/or cooling the two opposed SMA actuators (by applying a pulse-width modulated current), the guide wire can be forced to turn to one side or the other as dictated while the progress of its tip is followed on a real time fluoroscopic x-ray screen.

Table A1: Projects sponsored by Research Laboratories in 2003.

Projects for outside sponsors:
An Active Defense Robot for Practicing Free Kicks (soccer practice) (two projects)
A Dressing Station for Upper Bi-Lateral Amputees
A Multiple Station Extrusion Device (two projects)
An Inventory/Distribution/Transportation Synchronization Decision-Making Tool
A Software Tool for Use as Part of NASA Shuttle Simulation Training
A Mechanized Fire Hose Lay-up Device
Preparation of NASA Nanocomposites
Re-engineering of a Commercial Borescope for Space Applications
Projects for faculty:
An Interactive, Controllable, Demonstration of a Variable Speed Transmission
A Human Powered Electric Generator with Mechanical Energy Storage (two projects)
A User-Friendly, Computer Based System for Assisting Visitors in Finding People and Rooms in the College of Engineering (two projects)
Product development projects:
Commercialization of a Foot Activated Computer Interface
Commercialization of a Low Power Light Bulb
Commercialization of a Human Fatigue Sensor
Eight projects for regional student design competitions:
Seven Teams in the IEEE Robotic Competition (a 2nd and 4th place regionally)
One Team in the ASME National Design Contest (3rd place regional)

Table A2: Additional Projects For 2003.

THREE DEVICES DEMONSTRATING THE USES OF A MAGNETO-RHEOLOGICAL FLUID

Introduction

As noted above an MR Fluid is a liquid whose viscosity changes when a magnetic field is applied to it. The stronger the magnetic field applied to the fluid, the more viscous the fluid becomes. The fluids have been around since the 1950's but have found few applications until recently. When computers were used to control the magnetic field being applied to the fluid, some useful engineering applications evolved. The client's objective was to raise the awareness and interest of University of Houston students and visitors in Smart Materials by building an interactive display showcasing the properties and applications of an MR-Fluid. Three interactive MR fluid experiments were designed and fabricated: a magnetic-lift crane, a vibrating platform, and a disc brake. The experiments were designed to display the fluid's properties as well as a few of its applications. All three experiments are fully interactive with the user via a control panel located on the front of the display case. Safety was a key concern in the design of the experiments. Another important feature was designing a visually pleasing set of experiments that required low maintenance. Reference [7] provides more details.

Magneto-rheological Fluid Morphing Experiment

The MR fluid morphing experiment illustrates how the MR fluid solidifies when a strong magnetic field is applied to it. A pulley platform was built to hold the wire that raises and lowers an electromagnet into a vat of MR fluid. As the magnet is immersed in the fluid, the user has the option of turning on the current to the magnet thus producing a magnetic field in a portion of the fluid. The MR fluid solidifies in the vicinity of the magnet and is picked up as the magnet is raised. Once the magnet is raised, the current can be turned off. Without the magnetic field, the solid reverts to a liquid state and falls freely back into the vat and splashes, allowing the user to see this transition from solid to liquid. The electromagnet is attached to a metallic rod that runs through a linear bearing to prevent side-to-side movement of the electromagnet so the fluid will not be splashed outside the container. Two square rods were added to the platform. One prevents the rotation of the electromagnet, while the other provides a place for position sensors to be mounted. The full set up of this experiment is shown in Figure A1.

Vibration Damping Experiment

The objective of the vibration damping experiment is to show a direct application of the MR fluid to provide controlled vibration damping. The vibrating platform is shown in Figure A2. There is a DC motor on top of the platform that spins an unbalanced weight causing the platform to vibrate. A vertical metal plate is attached to the underside of the platform, and this plate extends into a long, narrow container of MR fluid. Around the container holding the MR fluid is an electromagnet that

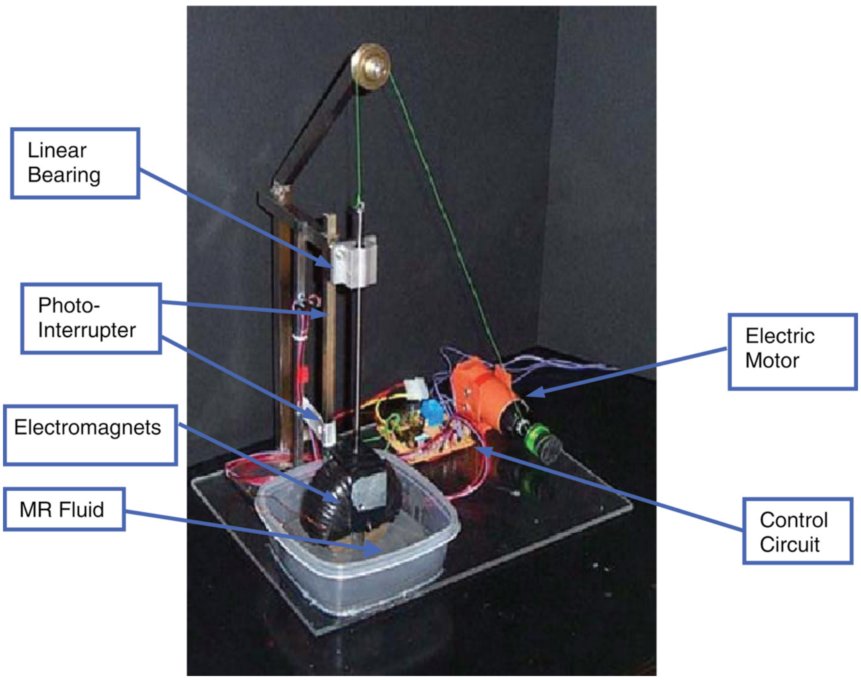


Figure A1: MR Fluid Morphing Experiment.

when activated, increases the viscosity of the MR fluid which restricts the movement of the metal plate, therefore damping the vibration of the platform.

MR Disk Brake Experiment

The main body of the disk brake (Figure A3) is composed of three different materials. The outer shell, containing the fluid reservoir, is constructed from clear acrylic to allow the enclosed disk and fluid to be

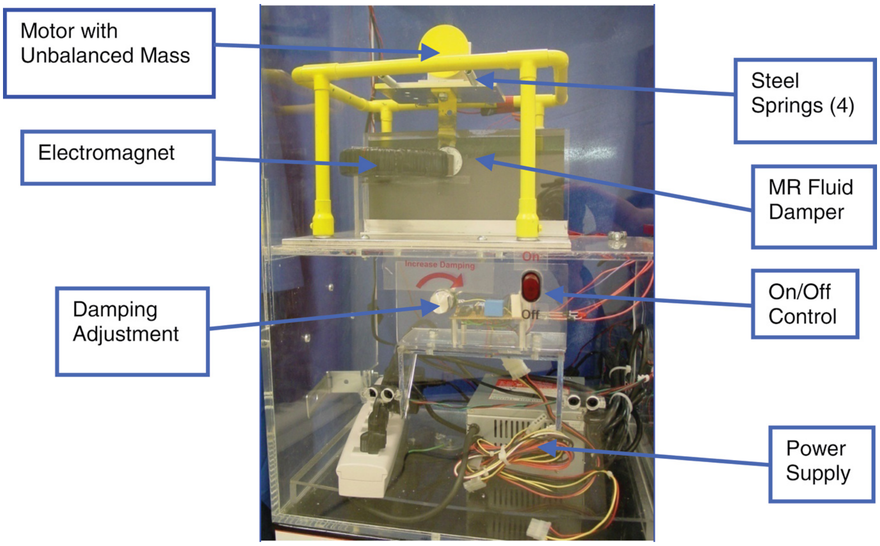


Figure A2: Vibration Damping Platform.

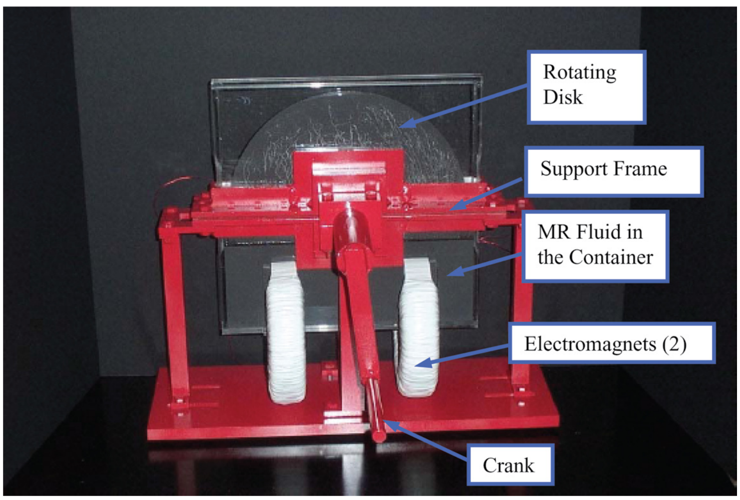


Figure A3: The MR Disk Brake.

visible. The main bracket, base, and supports are constructed from aluminum. Aluminum was chosen because it is unaffected by the magnetic field. The third part is the disk and crank assembly, and it was fabricated with 1018 carbon steel. The steel disk allows for some of the magnetic field to be spread out over a larger area to increase the stopping power of the brake. Two journal bearings were chosen to support the crank and disk on the stands, and automotive camshaft seals were used to seal the bracket to the crank. The whole rotating assembly is lubricated by automotive assembly lube. The fluid reservoir width is critical since making it too wide means that more current will be needed to ensure an adequate magnetic field is applied over the larger gap, and making it too small would mean a tighter tolerance on the disk to prevent rubbing on the fluid reservoir. Two thermistors are attached to the magnet cores to monitor the temperature. If the temperature of the magnets rises above a predetermined level, the experiment will shut down automatically. By turning the crank (in the center of Figure A3) the user obtains a direct indication of the fluid's "resistance" which, of course, increases as the strength of the magnetic field increases. The user has access to a knob that increases or decreases the current provided to the electromagnet, regulating the strength of the magnetic field applied to the fluid.

The Display Case for the MR Fluid Experiments

The three interactive experiments were mounted together in a display case as shown in Figure A4. The display case is fully interactive and self-explanatory. Nevertheless, instructions for each experiment are posted with the case. In addition, a brief background of the history of MR fluids is exhibited behind the experiments.

TWO DEVICES DEMONSTRATING THE USES OF A SHAPE MEMORY

Introduction

Shape Memory Alloy is the name applied to that group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature will return to their original shape. Only those alloys that can recover a substantial amount of strain, or that generate significant force upon shape transformation, are of commercial interest. One such material is a Nickel-Titanium alloy called Nitinol (NiTi). This particular alloy has useful electrical and mechanical properties, long fatigue life, and high corrosion resistance. This novel material has a very high resistivity that enables it to be actuated electrically by Joule (resistance) heating, making it an appealing type of actuator for numerous applications. On the microstructure level, Nitinol has the characteristic of changing from

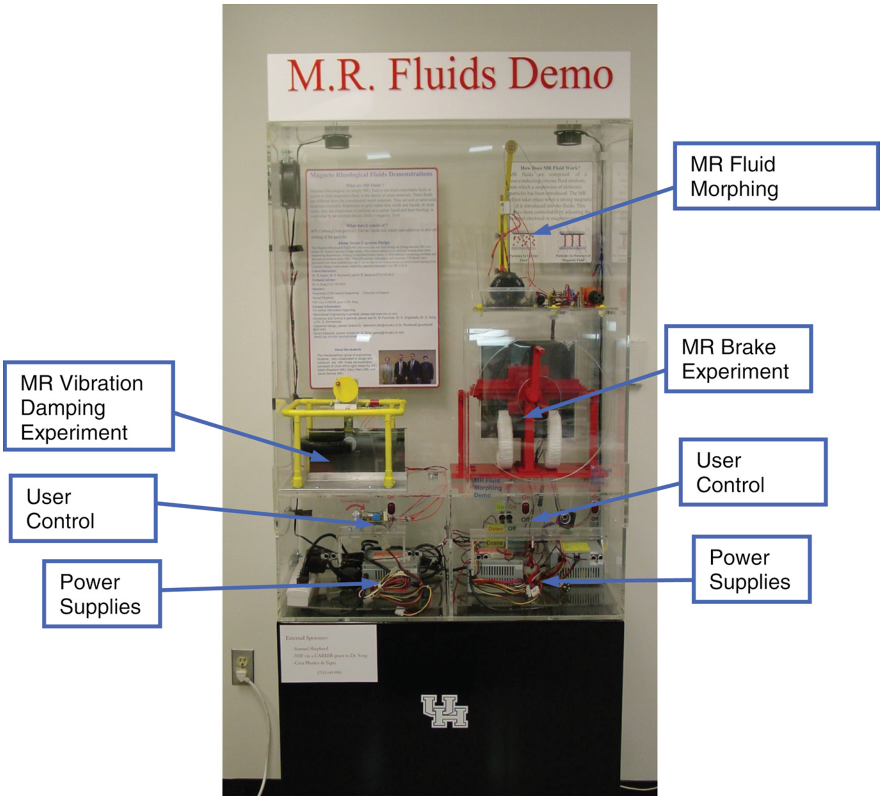


Figure A4: Display Case for the Three Interactive Experiments involving an MR Fluid.

a low temperature Martensite phase to a higher density Austenite crystal structure at a transition temperature of 90 °C. In the wire configuration, the transition results in 4% elongation as compared to the 0.01% or less elongation per degree centigrade for simple thermal expansion.

The two SMA interactive mechanical system demonstrations were designed, fabricated and then placed in an acrylic case. In the upper right portion (Figure A5) is an electrically controlled flexible limb. On the left side of Figure A5 is an electrically controlled weight lifting device. A control system was created for each demonstration, including the power sources (lower right side of Figure A5).

As illustrated in Figure A6, the flexible limb is a strip of flexible spring steel extending vertically downward, with attached eyelets that extend horizontally outward from the limb. The Nitinol wire actuator is threaded through the eyelets. The controlled, coordinated, alternating actuation of each wire allows movement of the limb in two directions. Whereas the original length of the wire is approximately 69 inches, the contracted length of the wire after activation is approximately 66 inches due to its 4% strain recovery. The contraction of either side of the limb displaces the end of the limb a horizontal distance of approximately nine inches, to either side. A set of springs has been added

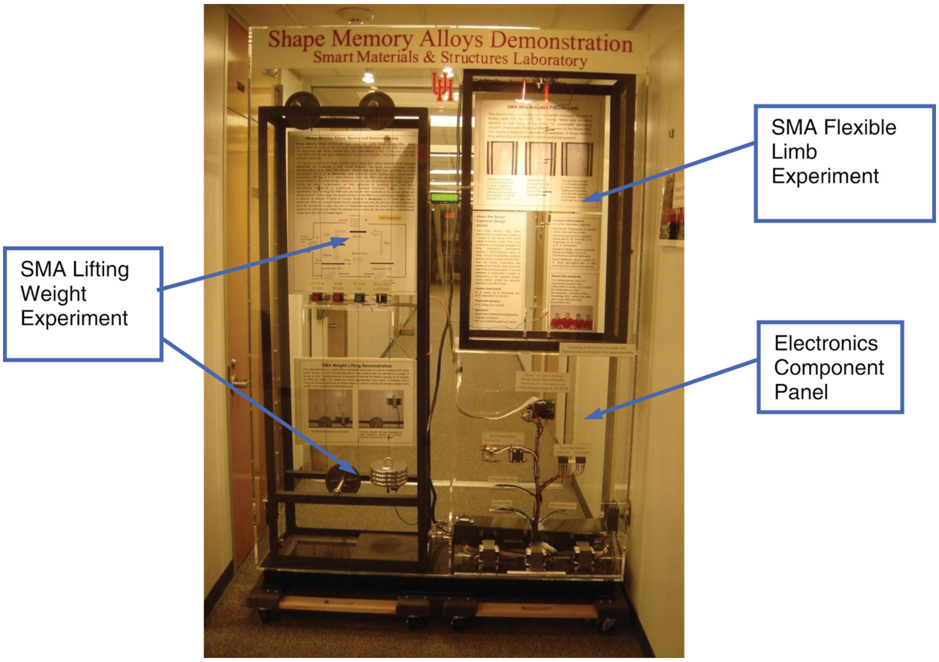
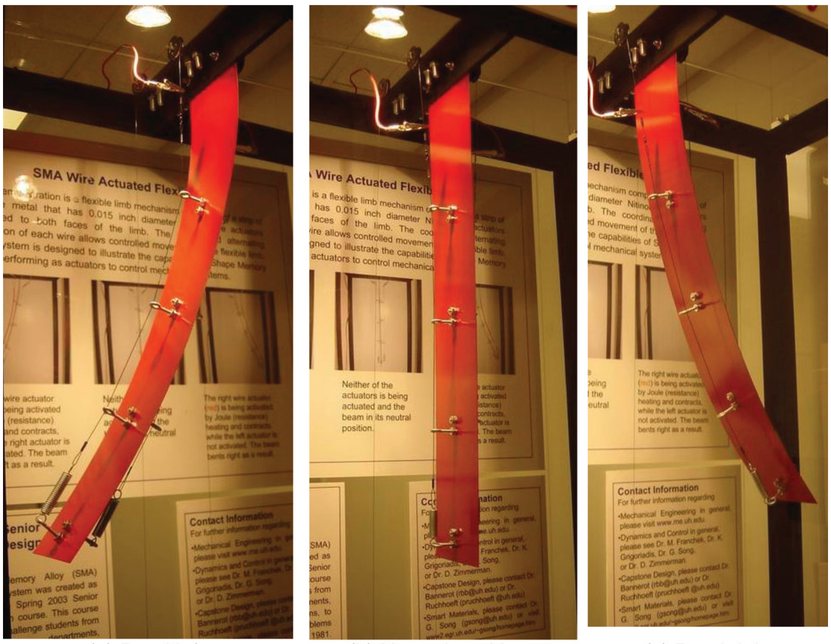


Figure A5: Interactive Demonstration and Display for Nitinol, a Shape Memory Alloy.



(a) Bend left (b) Neutral position (c) Bend right

Figure A6: Shape Memory Alloy Actuated Flexible Limb.

to each of the two actuators to limit the tension in the wire and prevent permanent deformation of the actuator. The method of activation is through Joule heating. In order to maintain stability and avoid over heating the actuator when the limb is sustained in a flexed position, the processor delivers the electrical power by pulse width modulation. The frame structure that houses the limb is made of carbon steel, with precision welds at each joint. The control for this device is a two-way, spring-loaded, rotating dial. The control allows the specific movement of the limb, in response to the direction of the turning angle in the dial indicator.

The weight lifting demonstration is illustrated in Figure A7, and it was designed and constructed with the intention of demonstrating the large force that the Nitinol actuator can exert. It was also designed to illustrate stability in a controlled displacement, and its maneuverability using an infrared distance sensor to provide displacement feedback. Again, Joule heating with pulse width modulation is used to prevent over heating of the Nitinol actuator and to ensure the displacement stability for the weight lifting demonstration. Seven strands of 0.015 inch diameter Nitinol wire pass over the three pulleys and are attached to the weights. In theory the twenty feet of the seven strands of wire will achieve a total linear extension/contraction of ten inches while supporting a weight of 30 pounds. The system uses 20 pounds, and the ten-inch extension was observed. The pulleys and shafts used for the system are made of ceramic and stainless steel materials respectively. The frame structure that sustains the shaft is made of carbon steel angle iron, with precision welds at each

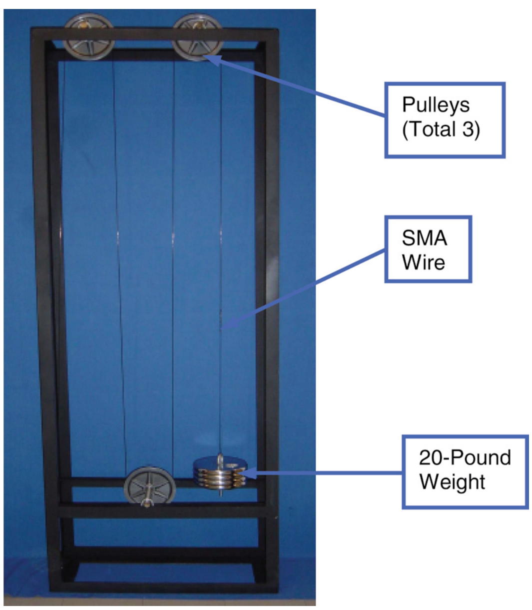


Figure A7: Shape Memory alloy Actuated Weight Lifting Device.

joint. This system is controlled using two push button controls that activate the lift, hold and drop actions. The acrylic case that contains the control platform and houses both mechanical systems was manufactured by an outsider supplier. As seen in Figure A7, the case was built with three compartments and special modifications for cooling and lighting. The bottom right compartment contains a retrievable acrylic platform that houses the processor, solid state relays, and transformers among other electronics. A control platform and a Liquid Crystal Display (LCD) have been installed in the front panel of the case to allow the user to interact with the system. The openings located in the lower extremities of the display case were designed for a pair of cooling fans that provide convective cooling to the actuators and electrical compartments.

The control system was designed in the following manner: The heart of the system that receives, processes, and delivers the signals and information is the microcontroller. The position of the weight in the weight lifting device is sensed with an infrared sensor located at the base of the case. This information is forwarded to the controller. With the location of the weight always known, the control system can override user instructions to extend an already "extended" wire. The microcontroller receives information from the control panel, and processes it using the guidance of the code written in Interactive C. With the assistance of the transformers, solid state relays and other assisting power amplifiers, the proper static or pulsating signals are delivered to the actuators. The same processor activates lighting and ventilation in predetermined time relays.

The control system is prepared to avoid an overload of power by implementing a set of fuses. Each mechanical system has its own individual power source, to avoid a complete system failure. Shape Memory Alloy literature is posted near the case to provide a sufficient understanding of Shape Memory Alloys and their potential functionality.

BIBLIOGRAPHY OF MULTIDISCIPLINARY COURSES AND PROJECTS

Multidisciplinary Courses (involving all or most students)

Harvey Mudd College has involved all engineering students (juniors to graduate students), working in multidisciplinary teams on about 25 industry sponsored projects a year, since about 1965.

A. Bright and J. R. Phillips, "The Harvey Mudd Engineering Clinic: Past, Present, and Future," *Journal of Engineering Education*, 88(2), 189–194, April, 1999.

Colorado School of Mines involves about 280 engineering students a year from all engineering disciplines working on 40 to 50 projects a year.

Catherine Skokan, David Munoz, Douglas Sutton, and Richard Burczyk, "Assessment and Evaluation of Engineering Senior Design at Colorado School of Mines," Paper no. 11822 presented in Session 3A at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

New Mexico State University involves students from industrial engineering, mechanical engineering and technical communications working in multidisciplinary teams since 2000.

Patricia Wojahn and Young Ho Park, "A Multidisciplinary Team Approach for Capstone Design Courses: Challenges and Lessons," Paper no. 11797 presented as Poster no. 9 at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

Smith College provides a capstone experience for their general engineering degree modeled after the program at Harvey Mudd College, in which teams of four students work on real-world engineering design problems sponsored by industry and government.

Susannah Howe, "Lessons Learned in the Inaugural Capstone Design Course at Smith College," *Proceedings of the International Conference on Engineering Education 2004: Global Excellence in Engineering Education*, Gainesville, FL, October 16–21, 2004. Available on Conference CD and posted: http://www.succeed.ufl.edu/icee/SessionIndex.html.

Grand Valley State University involves all students in four engineering disciplines taking a two-course capstone design sequence. During the second course multidisciplinary teams work on industry sponsored projects.

Jeffrey L. Ray, "Industry-Academic Partnerships for Successful Capstone Projects," Paper S2B-24 in the *Proceedings of the 33rd Frontiers in Education Annual Conference*, Boulder, CO, November 5–8, 2003. Search at http://fie.engrng.pitt.edu/fie2003/index.htm.

Howard University has a capstone course in mechanical engineering but selects additional students from electrical engineering, marketing (the College of Business), and art (College of Arts and Science) to work on one industrial sponsored project each year.

Lewis Thigpen, Emmanuel Glakpe, Gerald Gomes, and Terrence McCloud, "A Model for Teaching Multi-Disciplinary Capstone Design in Mechanical Engineering," Paper S2G-1 in the *Proceedings of the Frontiers in Education 34th Annual Conference*, Savannah, GA, October 20–23, 2004. Search at http://fie.engrng.pitt.edu/fie2004/index.htm.

Oakland University involves all the seniors from four engineering disciplines plus computer science working in multidisciplinary teams in a capstone course.

Michael Latcha, et al., "Melting-Pot Senior Design at Oakland University," paper no. 11884 presented in Session 6A at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

George Fox University uses a multidisciplinary capstone course for its general engineering program with concentrations in mechanical and electrical engineering.

Gary Spivey and Robert Harder, "Stating a Multidisciplinary Senior Capstone design Course," Paper no. 11890 presented in Session 2A at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

Multidisciplinary Courses (involving many but not all students)

Pennsylvania State University has provided an opportunity for students to integrate design, manufacturing and business by providing real (industry-driven) projects, a curriculum in Product Realization, and a state-of-the-art, hands-on learning laboratory since 1994.

John S. Lamancusa and Timothy W. Simpson, "The Learning Factory—10 Years of Impact at Penn State," *Proceedings of the International Conference on Engineering Education 2004: Global Excellence in Engineering Education*, Gainesville, FL, October 16–21, 2004. Available on Conference CD and posted: http://www.succeed.ufl.edu/icee/SessionIndex.html.

Worcester Polytechnic Institute has provided the opportunity for multidisciplinary teams for both on and off campus projects for a long time.

Fred Looft, "Capstone Design at WPI—An Evolution of Projects Based on Education," Paper no 11723 presented in Session 6A at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

University of Florida involves about 150 students from engineering, business and packaging science working on about 25 multidisciplinary projects a year.

R. K. Stanfill, G. J. Wiens, W. E. Lear, and E. D. Whitney, "Institutionalized University and Industrial Partnership in Multidisciplinary Design and Build: Product and Process Realization," *Proceedings of 2001 ASME IMECE*, November 11–16, 2001, NY, NY. Available on conference CD: Book #100517.

R. K. Stanfill and O. D. Crisalle, "Recruiting Industry-Sponsored Multidisciplinary Projects for Capstone Design," *Proceedings of the ASEE Southeastern Section 2003 Annual Conference*, April 6–8, 2003, Macon, GA. Available on conference CD.

R. K. Stanfill, G. J. Wiens, W. R. Eisenstadt, and O. D. Crisalle, "Lessons Learned in Integrated Product and Process Design Education", *Proceedings of ASEE Southeastern Section 2002 Annual Conference*, April 7–9, 2002, Gainesville, FL. Available on conference CD.

R. K. Stanfill, "Lessons Learned From Integrating Entrepreneurship into A Successful Multidisciplinary Design and Build Program," *Proceedings of the International Conference on Engineering Education 2004: Global Excellence in Engineering Education*, Gainesville, FL, October 16–21, 2004. Available on conference CD and posted: http://www.succeed.ufl.edu/icee/SessionIndex.html.

R. K. Stanfill, "Web-enabled System for Managing Student Applications for a Selective Industry-Sponsored Multidisciplinary Capstone Design Program: Integrated Product and Process Design (IPPD)," *Proceedings of the 2008 ASEE Annual Conference and Exposition*, June 21–25, 2008, Pittsburgh, PA. Search at http://www.asee.org/conferences/paper-search-form.cfm.

University of Puerto Rico at Mayagüez has provided an undergraduate product realization/manufacturing engineering option called the Learning Factory, an outcomes-based undergraduate curriculum integrated with laboratory facilities and industry partnership since 1994.

Lueny Morell, Jorge I. Vélez-Arocho and José L. Zayas-Castro, "Learning Factory at UPRM: Ten Years of Impact," *Proceedings of the International Conference on Engineering Education 2004: Global Excellence in Engineering Education*, Gainesville, FL, October 16–21, 2004. Available on conference CD and posted: http://www.succeed.ufl.edu/icee/SessionIndex.html.

South Dakota School of Mines and Technology provides a campus-wide opportunity (including six engineering disciplines) for students to work on industry-sponsored projects and national engineering competitions since 1998

Dan Dolan, Mike Batchelder and Jim Reynolds, "Multidisciplinary Teaming through Student Design Competitions." Paper no. 11876 presented in Session 5B at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

Binghamton University (SUNY) involves approximately 140 students from three disciplines (computer engineering, electrical engineering, and mechanical engineering) participating in a two-semester design sequence each year.

Roy McGrann, Colin Sellect, and Matt Laferty, "A Management Structure for Multidisciplinary Capstone Design Projects", Paper no. 12186 presented as Poster no. 30 at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available at conference CD.

Northeastern University involves engineering technology students in teams of about six from three disciplines but not all projects are multidisciplinary.

Francis A. DiBella, Randy August, Joel Weinstein, and Jerry Tapper, "A Description of an Integrated Capstone Senior Design Course with Teams of Mechanical, Electrical, and Computer Engineering Technology Students," *Proceedings of the 2006 ASEE Annual Conference and Exposition*, June 18–21, 2006, Chicago, IL. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Rensselaer Polytechnic Institute has completed forty-four industry sponsored projects (as of 2006) in the seven preceding years.

Richard Smith and Mark W. Steiner, "Integration of Real-World Multidisciplinary Design Experiences into the Capstone Experience," *Proceedings of the 2006 ASEE Annual Conference and Exposition*, June 18–21, 2006, Chicago, IL. Search at http://www.asee.org/conferences/paper-search-form.cfm.

University of Kentucky has involved 160 mechanical, electrical and computer engineering student (as of 2006) over the preceding four years in a continuing project (note recent collaboration with Aerospace Engineering Department at Oklahoma State U, below).

Jamey Jacob, James Lumpp, Suzanne Smith, and William Smith, "BIG BLUE: A Multidisciplinary Capstone Engineering Design Project," *Proceedings of the 2006 ASEE Annual Conference and Exposition*, June 18–21, 2006, Chicago, IL. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Oklahoma State University has involved about 90 aerospace engineering student so far (2007) in a collaboration with the University of Kentucky (above)

Suzanne W. Smith, Keith E. Rouch, William T. Smith, and Jamey Jacob, "Multi-University and Industrial Collaboration for Research-Oriented Capstone Experience", Paper no. 11815 presented in Session 7C at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

University of Nevada Las Vegas involves students from civil and environmental engineering, electrical and computer engineering and mechanical engineering in a year-long product development competition that started in 2004.

Ram Venkat, et al., "College-Wide Senior Design Competition: A Motivating Approach," Paper no. 12022 presented as Poster no. 25 at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

Montana State University has involved a limited number of teams composed of mechanical engineering and mechanical engineering technology students, as appropriate, to work on industry-sponsored projects since 2005.

Robb Larson and Vic Cundy, "Combined ME/MET Capstone Projects at Montana State University: Organization Issues, Case Studies and Lessons Learned," Paper no. 12182 presented as Poster no. 29 at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

Rice University involves students from mechanical, electrical and biomedical engineering (but paper mainly describes a single project).

David McStravick and Marcia O'Malley, "Improved Interdisciplinary Capstone Design Projects with Cooperative Learning in the Medi-Fridge Project," *Proceedings of the 2007 ASEE Annual Conference and Exposition*, June 24–27, 2007, Honolulu, HI. Search at http://www.asee.org/conferences/paper-search-form.cfm.

University of Detroit Mercy runs a pilot program begun in 2004 to combine a limited number of undergraduate students from mechanical and electrical engineering to design autonomous vehicles. Electrical Engineering graduate students were added in 2005.

Mohan Krishnan, Mark J. Paulik and Nassif Rayess, "A Multi-Disciplinary and Multi-Cultural Competition-Based Capstone Design Program," paper T2E-13 in the *Proceedings of the Frontiers in Education 36th Annual Conference*, San Diego, CA, October 28–31, 2006. Available at http://fie.engrng.pitt.edu/fie2007/index.html.

San Diego State University has a capstone course collaboration involving students in the mechanical engineering and the rehabilitation programs to complete products to assist physical challenged individuals participating in aquatic activities (with NSF funding). In three years 34 students have worked on 11 projects.

K. May-Newman, P. Newman, C. Sax, and U. Miyares, "A Partnership for Senior Design Projects in Biomedical and Mechanical Engineering," paper S1D-18 in the *Proceedings of the Frontiers in*

Education 37th Annual Conference, October 10–13, 2007, Milwaukee, WI. Available at http://fie.engrng.pitt.edu/fie2007/index.html.

Single Projects for Multidisciplinary Teams

Louisiana Tech involves primarily engineering and business, but other colleges as well, in the research, development and marketing of a product involving freshman through seniors. In the pilot stage.

Kelly Crittenden, "IMPaCT: Innovation through Multidisciplinary Projects and Collaborative Teams," Paper no. 11784 presented in Session 7C at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.

Farmingdale University (SUNY) describes a one-year project involving students in mechanical, manufacturing and electrical engineering technology.

Venkitaswamy Raju, "A Unique Capstone Project: Building an Aircraft," *Proceedings of the 2006 ASEE Annual Conference and Exposition*, June 18–21, 2006, Chicago, IL. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Arizona State University has formed student teams from mechanical and aerospace engineering technology for several years.

Alvin Post, John Rajadas, and Bradley Rogers, "Design, Fabrication and Testing of a UAV as a Multi-year Capstone Project," *Proceedings of the 2007 ASEE Annual Conference and Exposition*, June 24–27, 2007, Honolulu, HI. Search at http://www.asee.org/conferences/paper-search-form.cfm.

University of Wyoming describes one project for six engineering departments with 15 to 25 students volunteering each year for a two-year project: Automated Transit System for the Campus. A new project is expected every two years.

Charles Dolan and Ovid Plumb, "Interdisciplinary Capstone Design Program: a Case Study", *Proceedings of the 2008 ASEE Annual Conference and Exposition*, June 21–25, 2008, Pittsburgh, PA. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Embry Riddle Aeronautical University involved students from mechanical and electrical engineering and engineering physics.

William Barott, J. E., McKisson, and Darris White, "Organization of a Multi-Disciplinary Capstone Design Project for the SAE Formula Hybrid Competition," *Proceedings of the 2007 ASEE Annual*

Conference and Exposition, June 24–27, 2007, Honolulu, HI. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Eastern Washington University describes setting up a company-like atmosphere to develop and produce consumer products and run by the Department of Engineering and Design which grants eight bachelor degrees including one engineering degree in electrical engineering.

Mindy Breen and Jason Durfee, "Senior Capstone: A Cross-Disciplinary, Student-Centered Approach," *Proceedings of the 2006 ASEE Annual Conference and Exposition*, June 18–21, 2006, Chicago, IL. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Texas A&M University describes a one-time project for engineering technology and computer science students.

Steve Lu, Angie Price, and Jyjwen Wang, "The Dancing Marionette: An Interdisciplinary Capstone Design Experience for Engineering Technology and Computer Science Students," *Proceedings of the 2006 ASEE Annual Conference and Exposition*, June 18–21, 2006, Chicago, IL. Search at http://www.asee.org/conferences/paper-search-form.cfm.

Valparaiso University describes a one-time project involving a team of five seniors who designed built and installed a wind power, electrical energy generating system in Nicaragua in 2005.

Peter Johnson, et al., "Motivation, Inspiration and Economics of an International Service Project," Paper no. 11893 presented in Session 6B at the 2007 National Capstone Design Conference, June 13–15, 2007, Boulder, CO. Available on conference CD.