Succeeding at Teaching Interdisciplinary Design

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Abstract

For the past six semesters our departments of Electrical Engineering and Mechanical Engineering have attempted to engage students in collaborative interdisciplinary design experiences that are similar to real industrial design experiences. The interaction was achieved by linking two specific courses—the capstone design course in Electrical Engineering and the junior-level course in kinematics and dynamics of machinery in Mechanical Engineering. The choice of these particular courses as the focus of the collaboration, while perhaps fortuitous from a technical standpoint, was somewhat arbitrary, and was based solely on the desire of the two involved faculty to develop the cross-disciplinary collaboration. But the choice was fortuitous because the objective of the Electrical Engineering project routinely requires that considerable attention be paid to the design of some mechanism. Achieving a successful collaboration has been challenging; after six semesters, we are still not sure we have achieved success, but we are undoubtedly much closer to our goal. The purpose of this paper is to describe what did work and what did not, and thereby to assist others in implementing similar courses or experiences.

Introduction

One of the objectives for the collaborative design experience described in this paper is to give students experience in executing a real interdisciplinary project including performing project management functions such as compartmentalization of the design process, allocation of design effort to appropriate disciplinary experts, work scheduling, reporting, and performance evaluation. The challenges of accomplishing these things within an academic environment and across departmental boundaries are significant, perhaps even more significant than the challenges faced in an industrial environment. We will describe here the context and nature of the collaboration, the challenges that we faced in creating a successful collaboration, and changes that we have made to improve the experience. We, the two instructors of the involved courses, have worked diligently to constantly improve the quality of the interdisciplinary design activity, taking a kaizen—continuous improvement—approach [Lumsdaine]. We believe that substantial progress has been made, which motivates this paper.

Context of the Collaboration

The mandatory one-semester capstone design course in the Department of Electrical Engineering at the University of South Carolina, *ELCT 402–Electrical Engineering Project Design*, uses as its project focus the IEEE (Institute of Electrical and Electronics Engineers) student competition that is held each year at the IEEE Spring Southeastern Conference (SoutheastCon). The SoutheastCon student competition has consistently required design of a real-time sensing and control package for a mechanical platform. Most often, the mechanical platform takes the form of a mobile robot. Without any external collaboration the EE

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students had to design and develop the mechanical subsystem in addition to the electrical sensing and control suite. The blend of electrical and mechanical design requirements naturally called out for a cross-disciplinary interaction, which the authors accepted as a challenge. They met the challenge by linking the students enrolled in the EE capstone design course with the students in the mechanical engineering course *EMCH 332–Kinematics and Dynamics of Machinery*, which is a mandatory junior-level class in the ME curriculum. EMCH-332 focuses on the synthesis and analysis of mechanisms and machinery and covers such topics as mechanical advantage, gear trains, and synthesis and analysis of multi-link mechanisms (four-bar, crank-slide, etc.). For the past three years—six consecutive semesters—the authors have used this link to give the students a serious cross-disciplinary design-and-build experience. But it has not been easy, as we will describe. First, some background on the nature of the design projects.

IEEE SoutheastCon Competition

SoutheastCon is the annual IEEE Region 3 (Southeastern United States and Jamaica) technical, professional, and student conference where electrical and computer engineering professionals, faculty and students share information through technical sessions, tutorials, and exhibits. Part of the Student Program includes a head-to-head hardware competition among the participating schools. The competition format and rules are established approximately a year in advance. To provide some perspective on the design problems, we describe next the last two contests.

The 2001 competition, hosted by Clemson University, required development of an autonomous mobile robot that retrieved ball bearings from a 4'x10' playing surface. White navigation lines on a black playing surface formed a grid of intersecting lines. A total of 15 steel ball bearings were placed at particular line intersections. An infrared LED signaled the start of play, at which time the robots started to move to retrieve the balls and deposit them in scoring bins. The winner was the team that accumulated the most balls in their scoring bin. The mechanical challenges of the robotic platform included having a fast moving yet stable platform, and having a capability to pick up balls from the playing surface and deposit them in the scoring bins. The electrical engineering challenges included sensing the infrared LED that signaled the start of the match, autonomous navigation by line following, sensing the balls, and design and programming of a game strategy. Both the mechanical and electrical components yielded interesting design challenges, and the benefits of an interdisciplinary collaboration were readily apparent. Nineteen schools participated in the competition; the USC team finished fifth.

The Spring 2002 IEEE SoutheastCon was hosted by USC so design of the student competition was the responsibility of our own students. The theme of the conference was "Learning from the Past — Innovating for the Future", which inspired the students to select the video game PONG, one of the earliest forms of an electronic video game, as the theme for the hardware competition. The video game version of Pong, introduced in 1972, was based on the game of Ping Pong; the goal of which was for the two competitors to always return an incoming ball to the opponent. In Ping Pong, a point is scored whenever the ball goes past the opposing player. The hardware competition required robots to face off across a rectangular playing field to play a modified Pong game. Contestants were provided access to the signal from a video camera mounted directly above and looking down on the playing field. Robots had to determine the ball position and trajectory from the video signal and use that information to control the paddle to return the ball. The playing surface sloped from the center towards each end so that the ball could not stop in the middle of the table. This contest exercised a wide variety of electrical and mechanical engineering skills and was another very appropriate project for collaboration between the electrical and mechanical engineers. As the host school, USC did not compete, but instead officiated over the very spirited competition which attracted twenty-seven schools. Due to the richness of this particular problem, the instructor of the ELCT 402 class chose to assign the same project during the 2002-03 year.

The Collaboration

We have tried to structure the collaboration so that it is as project-independent as possible. This minimizes the difficulty of updating the instructions every year when the specifics of the competition change. To date, the collaboration has occurred during six semesters, using the two different design projects that were previously described. Changes in instructions to students have resulted more because of improvements in the collaboration than by changes in the project.

The first collaboration began during the Spring 2000 semester, when the project was that of the robotic platform for retrieving steel balls and placing them in scoring bins. This project was repeated for three consecutive semesters: Spring 2000, Fall 2000 and Spring 2001. The project changed during the Fall of 2001 to work out the bugs in the Pong game hardware competition before it was hosted by USC during Spring 2002. The Pong project has now been repeated for four consecutive semesters: Fall 2001, Spring and Fall 2002 and Spring 2003. Though the particulars of the design project changed, the fundamental nature of the EE/ME collaboration remained unchanged. We anticipate that sticking to the IEEE SoutheastCon hardware competition schedule will continue to yield an ever-changing landscape of hardware design challenges; yet will allow the design process and the challenges of inter-departmental collaboration to remain relatively static so that the fundamental nature of the collaboration will continue.

The collaboration has taken at least six different forms as we have tried to work out the problems that appeared each semester. The relationships between the EE and ME student teams have evolved through several stages from Lead Contractor/Consultant, to Lead Contractor/Competitive Consultants, to Lead Contractor/Captive Supplier, and finally to Lead Contractor/Competitive Supplier. The interdisciplinary collaboration has become more successful with each iteration. We will describe next some of the problems that were encountered, and the resolutions to each. The most significant problems are discussed last.

Problems identified and Resolved

The problems we encountered included:

A. The two classes met at different times
B. The two classes sometimes differed widely in number of students enrolled
C. Faculty expectations of students were different in EE vis-à-vis ME
D. The motivations of students were different in EE vis-à-vis ME
E. The relationships between the EE and ME teams were difficult to identify, and the difficulty of developing a fair grading procedure

A. Different Class Meeting Times

Both the EE and ME classes are offered every semester (which otherwise would present a yet more significant problem) but the ME class is always taught on Tuesday and Thursday, while the EE class meets formally only on Wednesdays.

Solution

We attempted to address the lack of synchronization by forming the ME teams so that at least one student from each team had the EE class time slot open, and forming EE teams so that at least one student on each team had the ME class time open. From the EE perspective, this posed significant logistical problems because there were other more significant issues at play during formation of the teams. While the ME teams were self-organized by the students, the EE teams were assigned by the instructor with consideration for a variety of academic and personality indicators. Adding the schedule parameters made the problem intractable for the instructor. In practice, we simply hoped that each team would be able to find their collaborators at some time.

B. Disparate class sizes

Typically the ME class enrolls about 25 students per semester and recently the EE class has enrolled between 10 and 20 students. Sometimes the disparity in class size is quite large; during one semester the ME class had 36 students and the EE class had only 8. Such extreme disparity in class sizes made it impossible to simply pair teams across departments without the ME teams being too large to be effective.

Solution

The class size disparity has been addressed in two ways.

1) By assigning more than one ME team to each EE team and organizing the collaboration so that the ME teams served as competitive vendors to the EE teams.

2) By partitioning or compartmentalizing the design task along traditional disciplinary boundaries and setting rigorous standards for the interfaces so that each ME team was competitive with other ME teams and each EE team was competitive with other EE teams, yet every product of an ME team worked with every product of an EE team. This is the latest iteration in this solution process and the success is not yet known. More will be said of it later in this paper.

C. Incompatible Semester Plans

Originally the EE teams were required to demonstrate some portion of their project at mid-term. This nearly always included some aspect of the mechanical system. And since the mechanical system was used as the "testbed" for the electronics, virtually every EE team wanted to construct the mechanical system first thing. The organization of the ME class, following the organization of the textbook, dealt first with the theory of four-bar mechanisms (which were generally not too relevant to the design project) and last with rolling and dynamic systems. This meant that the ME students were not prepared to *do* the mechanical design until well into the semester—after the EE teams needed to have hardware built.

Solution

Topics germane to the design exercise were moved to the beginning of the semester. And as a result of other changes, the EE teams have a less compelling need to interface to mechanical hardware early in the semester.

D. Different Expectations and Motivations

The initially widely different expectations of the EE and ME faculty, and hence widely different motivations of the EE and ME students, caused significant problems. The EE class is all about successful completion of the project; graduation depends on a successful project performance so the EE students are highly motivated. Often they begin the semester with a pre-conceived notion of what they will build and they are often (at least psychologically) deeply committed to their own concept. In contrast, the ME class initially allocated only 1% of the semester grade to the design effort, which was run as a mini-project (or a maxi-homework). The danger of making the project count more, from the ME perspective, was that the students would sacrifice learning the other imperative course content, which was judged to be an unacceptable trade-off. So the students were significantly less motivated to succeed.

For four semesters the deliverable products of the ME teams were paper designs. This caused more than a little friction between the EE and ME teams, regardless of whether the collaboration was as "advisor" or "contractor", because the EE teams often felt that the ME teams delivered incomplete or unworkable paper designs. Although the deliverables included a written description of the design, mechanical drawings, bills-of-materials, and kinematic and dynamic computer models using Working Model™ software, still a paper design is a long way from hardware, especially when fabrication details or methods were not given, or the methods were out of reach of the EEs.

Solution

The motivational and deliverable problems were fixed when three changes were made simultaneously.

- The ME student participation was changed from mandatory to voluntary.
- The ME students were allowed to substitute any one of their 5 grade items (20% each for 4 exams and homework) with the project grade.
- The ME students were required to deliver working machines rather than just designs.

The first semester this change was made 45% of the class volunteered to work on the project. The next semester, 95% of the students volunteered. With the ME students now willing participants in the project, scheduling meeting times was no longer an issue; the students always found a way to meet. For the first time since the inception of the collaboration, the ME students were highly motivated to produce good, tangible, functional mechanical systems. By providing hardware, they literally had to stand behind what they delivered.

E. Relationships between the teams

It was not immediately obvious what should be the best relationship between the ME and EE teams. Should the ME's serve as consultants to the EE teams? Should the ME teams be competitive with each other? Should they compete for the privilege of having their design selected by the EE teams? Should the ME students be an integral part of the EE teams? We didn't know initially, but we have now tried many different approaches and we think we now have a successful formula. It is successful because it is based to a large extent on compartmentalization of design elements along disciplinary lines much as would be done in industry. We will describe next the historical evolution of the team relationships to better explain what does and does not work.

Initially, the ME students were told that the EE students were the *drivers* of the project and that the ME students were to act as "consultants" to their "customers". The ME teams should respond to the needs and requests of the EE teams. If there were more ME students than EE, then two teams of MEs were assigned to each EE team and the two ME teams were competitive consultants to the EE teams. The EEs evaluated the ME designs and chose the one they believed would best fit their needs.

During this time the EE students were responsible for providing some grade input to the ME professor. The EE teams were asked to develop the grading criteria, which is shown in Table 1. The grading criteria weighed heavily the ability of the MEs to collaborate with their EE counterparts, and also the value the MEs added to the perceived overall performance of the end product (the machine).

EE student team grading of ME student teams (Paper Design)	Points
Professionalism	
Available for consultation/meetings	10
Responsive to email or other communications	10
Quality of Design	
Design met the product requirements	10
Design adhered to the interface specifications	10
Design was practical to implement and accomplished the desired function	10

Design was especially innovative and provided un-requested but valuable functionality that yielded a better-than-anticipated product	10
Quality of Documentation	
Final design report was clearly written and appropriately organized	10
Bill of materials was complete, with appropriate callouts on the drawings	10
Drawings were clear and comprehensible (but not necessarily computer drawn)	10
Working Model simulation was well-implemented	10
Total Score	100

Table 1 – Student-developed Grading Criteria for Paper Designs

During the semesters when this approach was used, the EEs generally disregarded the designs of *both* ME teams and built systems of their own designs. The EE students complained that the ME designs were unworkable, impractical, and incomplete, that the computer models were not realistic, and that they would be difficult to implement. Meanwhile, the ME students complained that the EE students already had their minds made up about what they were going to build and so the EE students did not give any consideration to adopting the ME designs. A major flaw was that the ME designs were delivered too far into the semester for the EEs to give them due consideration. The low grade credit given to the ME teams was certainly also a factor. There was much acrimony and if the students learned anything about interdisciplinary projects, it was that such projects are difficult, frustrating, and probably unsuccessful.

Solution

In the next phase, we addressed this shortcoming by having the ME students deliver real hardware and increasing the grade credit. The advantage of doing this is that the ME students are forced to go all the way through the design process to the stage of hardware development. Another advantage is the EE teams get to truly focus on the electronics and controls aspect of the hardware design project. Under this scheme, the relationship between the teams has taken two forms. In the first, each ME team had to deliver a working piece of hardware to an assigned EE team. This posed the serious disadvantage that the fate of the EEs semester grade fell into someone else's hands. If an ME team did not deliver hardware, the EE students could not prove that their system worked, and they could not compete in the end-of-term competition. This was a real threat since the ME participation was voluntary. In the second scheme, we addressed the potential for non-delivery by requiring that all systems, mechanical and electrical, be designed to a strict interface standard (see later) so that any electronic controller could drive any mechanical system. This averaged the hazard of non-delivery across all groups and in the end, since only two mechanisms are needed to have an effective competition, the failure-to-deliver risk is deemed negligible.

In a further improvement that mimics industrial practice the students are now required to form a “standards committee” composed of representatives from every team (both ME and EE alike) to define a set of standards that are ratified by all of the groups. During the first semester at trying this, we eased the transition by specifying a standard motor for the actuator. In subsequent terms we may relax that requirement. At the end of the term, as part of the grading criteria, each EE team must now show that it can connect to and use each mechanical subsystem that is built to the interface requirements (but they get to select a particular machine for the end-of-term competition.)

Now, as a regular in-class exercise, the EE students develop the criteria for grading the ME hardware. These criteria are made known to the ME teams before they go about their designs. The EE students brainstorm through the attributes they think are important, rank order them, and develop methods for assigning weighting factors and then numerical scores to the items. Table 2 shows the grading criteria the students developed during the Fall 2002 term.

Rank	Attribute	Points
1	Speed of Carriage	20
2	Return Speed	20
3	Power Requirements	20
4	Quality of Construction	20
5	Return Variation/Control	10
6	Meets Electronic Interface Specs	5
7	Accommodation of sensors	5
8	Appearance	5
9	Stability of System	5
10	Effort	3
11	Durability	4
12	Adaptable Mounting and Fit	3
	TOTAL	120

Table 2 – Student-developed Grading Criteria for Delivered Hardware

The EE students came up with Table 2 by considering several factors. They reasoned that the delivered hardware had to minimally meet attributes 1–4 in order to just play the game, so they were weighted heavily. Attributes 5–7 were judged "extras" that might allow a team to win the game. Finally, attributes 8–12 were judged to be worth extra credit.

Mistakes Made—Lessons Learned

Since the beginning of the EE and ME collaboration in the spring of 2000 the instructors have constantly tried to improve the quality of the interdisciplinary design activity by taking a kaizen—continuous improvement—approach [Lumsdaine]. During the first semester, the ME students' role was that of an engineering assistant, and the ME professor did not address the project nearly enough in class. Since the project counted as a single homework grade, approximately 1% of a student's semester grade, the ME students did not take it seriously and did not invest enough effort to make the collaboration bear fruit. During subsequent semesters both the ME and EE instructors started to place greater emphasis on the collaborative aspect of the interdisciplinary project. The ME students started to see their role as a mechanical consultant to the project, and the ME instructor devoted a greater number of class hours to discussing the project. The design process [Ulmer, Pugh] was emphasized, and the EE students were identified as customers. Also engineering content specifically germane to the project was addressed in the class using the ME Kinematics text [Norton]. The ME grade was now based on three grade components i) concept sketches and benchmarks, ii) powerpoint presentations of the design ideas using Working Model™ software, and iii) the final design report including bill-of-materials and all drawings. The project now counted as 5% of the total course grade. But there was still a lot of room for improvement.

In the Fall of 2002 a drastic change was made; ME participation became voluntary, with the project grade replacing any other grade component, amounting to 20% of their final grade. Also, the MEs built their own mechanisms and had to deliver the actual hardware. The MEs paid for all mechanical components themselves, which naturally kept costs down and forced more creative solutions. With the MEs totally responsible for the mechanical aspect, the EEs focused on the electrical design and control algorithms. The mechanical devices were delivered in mid-semester, and the ME students manually operated them to play a game of Pong. The student comments were much improved and there was more teaming because the ME students took a greater vested interest in the project.

Conclusion—Where to go from here

The success of the EE and ME interdisciplinary design effort improves with each passing semester. During the current term each mechanical system and electrical controls system will be "plug-and-play" compatible, meaning that standard electrical and mechanical interfaces will allow for easy swapping of different mechanical systems. Now every team has a deep stake in the end of term competition because winners (and losers) will be identified in both the EE and ME camps.

We anticipate to keep the activity voluntary for the ME students, with the 20% grade replacement strategy. In addition, the subject of gears, cams and motors, traditionally taught later in most kinematic and dynamic classes, will now be taught at the beginning of the semester.

Student comments and instructor evaluations are one obvious way to measure the success of this interdisciplinary venture, and will be formally compared in the future. But perhaps an even better metric will be if the USC teams begin to consistently finish higher in the SoutheastCon hardware competition.

References

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Appendix

Parts, Bits and Pieces

We try to ease the students' learning curve by suggesting sources for parts, bits, and pieces they will need to construct their systems. For mobile robotic platforms, such as the ones used in the ball bearing retrieving project, students were pointed to kits such as those found at Lynxmotion, Inc. For all structural components, the students are encouraged to use light gage aluminum or other types of material that can be easily cut, drilled and fastened. One such easily "machinable" material is a high-density PVC foam board called Sintra (see GE Polymershapes, keyword "Sintra"). A 5mm thick, 4'x8' sheet of the foam board is available locally for about $42 per sheet. Hardware stores, hobby and model shops, ToysRUS, Grainger and McMaster-Carr are also local companies in most metropolitan areas which have parts useful in the hardware design. Most of these companies also have websites for the students to browse. Resources for hardware can be found at numerous websites, such as: www.lynxmotion.com, www.gepolymershapes.com, www.jameco.com, www.alliedelec.com, www.mpja.com, www.sdp-si.com, and www.mouser.com.

For the most up-to-date links for hardware resources, it is suggested you visit the USC Electrical Engineering Department website (http://www.ee.sc.edu/) and look under courses, ELCT-402.

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