A Teaching Framework for University-Based Multidisciplinary Systems Engineering

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Project Summary

We propose to develop a teaching framework for large-scale, multidisciplinary university engineering projects, with the goal of providing students with a design experience more reflective of industrial projects than typical design courses. We will implement and test this curriculum in a new project-based course in multidisciplinary systems engineering. The key features of our proposed course are that it will:

1. *Generate a large-scale, operational product* requiring months of development and the efforts of 20-30 students in a scale and environment much like students will encounter after graduation. The course will present the fundamentals of modern engineering in the context of a substantial design project that will differ from year to year.

2. *Integrate students from a variety of disciplines and across all academic years* to reflect the range of experience levels and backgrounds found in real-world projects. Students ranging from freshman to seniors will collaborate to conceive, design, implement, and operate a system involving electrical, information, and mechanical engineering components.

3. *Incorporate electronic tools for project management* including web-based systems to expose students to the skills required to manage large projects. Specific tools will be provided for setting project goals and objectives, managing interfaces between component subsystems, working in design teams, and tracking progress against tasks, and teaching modules addressing these project management principles will be developed.

These features build upon our experiences with traditional engineering and design courses as well as the development of Caltech's DARPA Grand Challenge entry, which utilized more than 60 undergraduate students at all academic levels over the course of a year and required the development of prototypes for many of the tools needed for this course. The primary objective of our effort is to develop the materials and pedagogy for new ways of teaching engineering that will substantially change the learning experience for undergraduate engineering majors.

To allow implementation of a truly multidisciplinary curriculum in an often discipline-focused university environment, we will develop a system by which traditional departmental curricula can be adapted to complement our systems engineering approach rather than be supplanted by it. Subsystem design will take place within modified versions of departmental design courses, with an umbrella course in systems engineering serving to coordinate the efforts for two terms and culminating in a third term in which the final design will be integrated and built. This coordination will have the secondary effect of being a formal opportunity for faculty from various departments to get together and devise an exciting interdisciplinary project and then see it through prototyping and operational stages. Example projects could be an autonomous desert racing vehicle such as was successfully built by an undergraduate team at Caltech in 2003-2004, a robotic mine clearing vehicle for operation in dangerous regions worldwide, or a self-contained glider to cross the Pacific Ocean.

Broader Impact In addition to providing the students who take this course with a unique exposure to a large-scale engineering project, we believe such a course can substantially contribute to a change in the culture of undergraduate engineering education. Engineers today are increasingly called upon to work in multi-disciplinary, mixed experience teams, but most university design projects are still heavily discipline-focused and taught with students in the same year of study. The tools and curricula we propose to develop will provide both an example of how design courses can work across disciplines and academic years and tools for project management that will enable others to create similar courses.

1 Introduction

Engineers today are increasingly called upon to design and build complex systems in which a "black box" approach to subsystem design no longer suffices. Instead designers must have an awareness of the overall system and the implications their decisions have on the whole, taking a multi-disciplinary *systems* perspective. As noted, for example, by the CDIO Initiative [1, 2], a gap has opened in recent times between engineering education and practice. This gap is due in part to the heavily discipline-focused nature of most engineering programs while real-world projects require multidisciplinary thinking. If we examine Boeing's "Desired Attributes of an Engineer" [3], we see items such as "a good understanding of engineering science fundamentals" and "a good understanding of design and manufacturing processes" that are thoroughly addressed by most engineering degrees, but also "a multi-disciplinary, *systems* perspective" and "a profound understanding of the importance of teamwork," attributes often neglected by traditional curricula.

In the proposed program we seek to define and test a framework for design projects that will help students both to achieve a better knowledge of their chosen engineering discipline and to understand how this discipline interacts with others in the design of modern complex systems. We also wish to integrate students from all academic levels into the design process to introduce students to modern engineering at an earlier stage in their education and to provide more senior students with leadership and project management training.

The proposed work will build on existing efforts such as the CDIO Initiative, which focuses on putting engineering fundamentals in the context of practical design projects, and studies on "design-build-test" based courses [4] and interdisciplinary learning [5]. We feel there is room to expand on this foundation in several key directions. Most engineering programs incorporate some kind of senior-level capstone design course, and some attempt projects on a scale similar to that which we propose. Most often, however, such courses reside within a single department, choose projects that rely primarily on the department's specialty, and are targeted only at advanced students. Efforts have been made to introduce students to engineering principles as early as the freshman year [6, 7], but these are frequently limited to relatively simple projects due to the inexperience of the students.

We envision a new curriculum that approaches the problem of engineering design education in a different way. Like capstone design courses, our courses will be project-based, but will be much larger in scale and will emphasize *systems* engineering. Teams of 20-30 students of all engineering disciplines will collaborate to design and build a *complex* engineering system over an entire academic year. During the first two quarters of the year (or first semester, if appropriate), students will attend project meetings and learn basic tools for project management while participating in subsystem design through modified versions of existing design courses in Computer Science, Electrical Engineering, and Mechanical Engineering. During the third term, the entire team will build, document, and demonstrate the course design project. Students of all academic years will participate, providing realistic engineering experience to students very early on in their academic careers and leadership and mentoring opportunities for senior students.

Program Goals. The long termgoals of this project are to

- G1 Develop the materials and pedagogy for a new way to teach engineering that will substantially change the learning experience for undergraduate engineering majors.
- G2 Provide students with a large-scale, multidisciplinary design experience reflective of the projects they will encounter in their professional careers.
- G3 Develop a new approach to university project management that is practical for university-scale use while teaching the principles important for project management in the professional workplace.

(a) Bob, Caltech's DARPA Grand Challenge entry at the Qualification, Inspection, and Demonstration pre-race event.

(b) Caltech's final DARPA Grand Challenge team. Over 60 students worked on the project at some point during its development.

Figure 1: Caltech's DARPA Grand Challenge effort. Over a period of one year, Caltech undergraduates worked to design, build, and operate a full-scale autonomous mobile vehicle to compete in a race through the Mojave desert.

These goals will build upon our experiences with traditional engineering and design courses [8] and research projects such as the 2004 DARPA Grand Challenge [9], shown in Figure 1. Additionally, they will require an integration across disciplines and departments that will expand on interactions already taking place.

2 Program Plan

In this section we describe the specific objectives and challenges we will face and the approach that we plan to take to meet the program goals.

2.1 Objectives

We have several concrete objectives designed to provide a path to the goals outlined above:

- O1 Develop and disseminate a set of teaching materials for large-scale multidisciplinary university engineering projects. These materials will address both the technical curriculum and techniques for implementing a cross-department, large-scale, project-based engineering course.
- O2 Conduct two iterations of a prototype systems engineering course based on the above teaching materials and document our experiences. This documentation will include a description of the projects attempted and the outcomes and lessons learned for future iterations of the course.
- O3 Produce and document a suite of electronic tools and accompanying teaching modules suitable for organizing and managing university-based engineering projects. In addition to their practical use for organizing and managing projects, these tools will be used to illustrate the principles of project management without incurring the educational overhead required to teach professional tools in detail.
- O4 Disseminate our results among a broad group of engineering educators across the country.

Multidisciplinary Systems Engineering GOTChA Chart

Goals	Technical Challenges
[G1] Change the learning experience for undergraduate engineering majors [G2] Provide students with a large-scale, multidisciplinary design experience [G3] Develop a new, practical approach to university project management	[TC1] Organizing a diverse group to complete a large project in a resource-constrained environment [TC2] Adapting course structure to existing departmental curricula [TC3] Creating a curriculum adaptable to the needs of diverse institutions
Objectives	**Approach**
[O1] Develop a set of teaching materials for university engineering projects [O2] Conduct two iterations of a project engineering course [O3] Produce a set of electronic tools for university project management [O4] Disseminate results among a national audience	[A1] Refine and document our use of Bugzilla, Wiki, and chart templates [A2] Write an instructor's manual for project-based systems engineering [A3] Employ an umbrella course structure to leverage existing classes [A4] Draw team leads from an advanced course in Project Management

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Figure 2: GOTChA chart for multidisciplinary systems engineering curriculum. GOTChA charts are an organizational tool we have found useful for managing university projects.

2.2 Technical Challenges

To achieve our objectives we must overcome several technical challenges. These challenges can be broadly categorized into two groups, one directly related to satisfying our educational goals and one that stems from the large scale and interdisciplinary nature of the material we intend to teach.

Educational challenges stemming from our objectives are those inherent in bringing together a large group (20-25) of students with widely varying abilities and experience levels to complete a significant project in a time- and resource-constrained environment. Over a single academic year the design team will need to design, document, and build a complex system such as an autonomous mobile vehicle. We will also need to devise a means of fairly monitoring and evaluating student and group performance without simple evaluative tools like homework and exams that fits within the grading schemes in use at most universities today.

Our projects will be inherently multidisciplinary and cooperation among traditionally discipline-oriented departments will be critical. Challenges deriving from these requirements include devising a course structure that complements the curriculum already taught at the discipline level and that will allow participation of a diverse group of faculty within their existing teaching requirements. We also realize that bringing a large-scale project such as we propose to completion may require more resources than are traditionally devoted to design courses at this level. To address this issue we will need to create a curriculum that is scalable to fit the needs and resources of diverse institutions.

2.3 Approach

In this section we describe a few key features of the approach we will take to address the challenges outlined above.

Electronic Tools for University Project Management. To address the challenge of organizing and guiding the team of students in a constrained environment we will develop a set of electronic

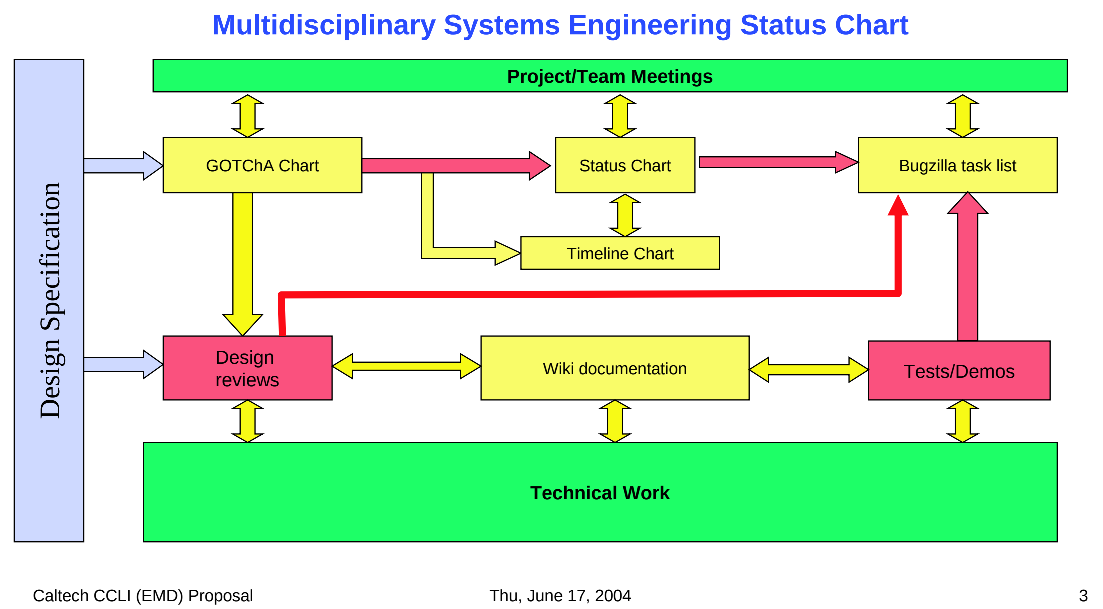

Figure 3: Status chart for multidisciplinary systems engineering curriculum. Each block corresponds to a module in our framework. Color codes are used to represent the current status of the pedagogy and tools.

tools suitable for projects of this size. The idea behind the tools is twofold: to provide an easy-to-use suite of software suitable for both classroom and laboratory use on projects of small to moderate size, and to illustrate the *principles* of project management without incurring the educational overhead required to teach more advanced tools in detail. To complement this development we will create teaching modules introducing both the tools and the design principles they address.

We plan to make use of two specific tools that we have already prototyped through the 2004 DARPA Grand Challenge effort. The first is Bugzilla [10], a publicly available, web-based bug tracking system that can be used for managing tasks in a team-based setting. The second is Wiki [11], another web application which allows groups of people to edit and maintain documentation on the web. Both of these tools allow a group of students to maintain searchable databases of tasks and documentation in a simple, easy-to use fashion.

We have also begun prototyping and testing several project management chart templates that can be use to present project plans and report progress. *GOTChA charts* are used to summarize the Goals, Objectives, Technical Challenges, and Approach for a project or team. *Status charts* describe the modules of work that a team is responsible for, along with the individual owner and status of the components. Finally, *timeline charts* allow a long term view of the project timeline and major milestones.

Strategies for Student Evaluation.

We will use several tools for evaluating student performance and progress in the absence of traditional homework and exams. Students will be expected to present their work at several design reviews, with the most important being a Preliminary Design Review (PDR) at the end of the first term, and a Critical Design Review (CDR) at the end of the second term. A critical aspect of these design reviews will be interaction with experts drawn both from faculty and nearby industry such as JPL. At these times students will also be given the opportunity to assess one another's performance using a review form we will provide. Students' grades will be based on both of these review techniques as well as their documentation and interactions with the teaching staff. Peer reviews and written assessments from the teaching staff and professional reviewers will be given to each individual and to the team as a whole. We will also investigate the use of recent results in the application of applied psychology metrics to measuring team effectiveness [12].

An Umbrella Structure for Multidisciplinary Design Courses. Our course will be organized with an umbrella structure, illustrated in a timeline format in Figure 4, to best fit in with existing discipline-based courses. During the first two terms of the course, students will take modified versions of existing design courses in computer science, electrical engineering, and mechanical engineering as determined by their interests. Rather than focusing on detailed design of a discipline-specific product, the courses will be used to develop requirements and preliminary designs for the major subsystems of the overall project. This structure will allow us to integrate with existing departmental curricula and within current faculty teaching requirements. The umbrella course will be used to conduct project meetings across disciplines and teach principles of project management. In the third term, the entire team will build, document, and demonstrate the course design project.

Engineering Project Management Course. In addition to the main design course, we will separately develop a course in “engineering project management.” In the first year this course will be open only to graduate students, but in subsequent years it will be open to upper-division undergraduates who have taken the design course in previous years. Lectures in this class will focus on setting and tracking objectives, managing a schedule, and organizing an engineering team, with particular emphasis placed on the electronic tools described above. Students in this class will be subsystem leads and will be responsible for managing a portion of the project. Drawing student managers from this pool of students who have some design experience will help us to address the organizational challenges of leading the project.

2.4 Implementation Timeline

We anticipate that the following milestones will be achieved over the course of the program. While the details of these milestones will certainly change in the course of our work, they provide our current plan for how the educational activities will proceed.

Year One. In the first year of the program, we plan to complete the following activities: (1) creation of draft instructor’s manual for multi-disciplinary systems engineering course; (2) initial iteration of design course numbered CS/ME/EE 75 using 2005 DARPA Grand Challenge as the project, adapting current curricula and tools developed for 2004 DARPA Grand Challenge; (3) documentation of lessons learned from this experience and a “wish list” for improvements to project management tools; (4) summer undergraduate project to refine project management infrastructure in the form of electronic tools customized for university projects; (5) selection of major project for second year of program.

Year Two. In the second year of the program, the following additional activities will be completed: (1) revision of draft instructor’s manual based on lessons learned from year one; (2) second iteration of design course incorporating improved project management tools and based on a new project; (3) first iteration of design course at a partner institution; (4) selection of major project for third year of program.

3 Program Outcomes and Deliverables

In addition to designing and carrying out the courses described above, we will have several specific deliverables to meet our objectives.

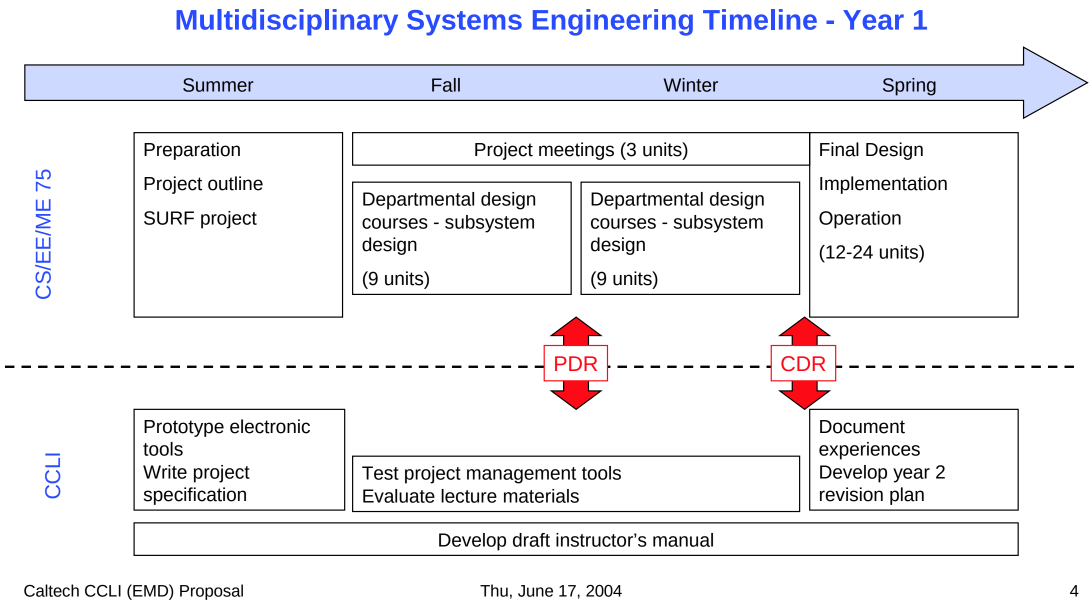

Figure 4: Timeline for multidisciplinary systems engineering curriculum development and initial implementation.

Instructor's Manual. Based on our experiences developing and teaching this course, we will write an instructor's manual for project-based systems engineering. This manual will have two major components. The first component will be a technical curriculum addressing project organization and management, including a description of the electronic tools we will develop as part of this program. The second component will be a set of guidelines and techniques for implementing a large-scale, cross-department, project-based engineering course.

Kit for Web Based Project Management. After refining our electronic tools for university project management, we will prepare, document, and make publicly available a kit for web based project management. This kit will contain a website template with implementations of Bugzilla and Wiki that can be easily installed and maintained by a non-expert.

Evaluation Report. To maximize our potential to learn from our experiences conducting this course we will create several opportunities for evaluation of our progress and document the results. First, we will used customized surveys at the beginning of the course and during midterms and finals each term to evaluate progress against our learning objectives against baseline knowledge. Second, we will complement these surveys by bringing in a facilitator at least once each term to discuss the course with the students. The goal of this interaction will be to generate more extensive feedback from the students than we may obtain from the course surveys. The facilitator will be able to speak directly with the students to draw out more detail on comments and provide expert advice on how the course might be improved as we go along.

To complement the PDR and CDR activities included in the course, we will have similar reviews of our course structure with outside experts. These experts will at minimum have attended the design reviews and can offer their views on how well the project is being managed and how effectively the students are being taught engineering skills. They will essentially represent our educational customers, that is, the people who will eventually be hiring new engineers. As with customers on any engineering project, we will present to them our approach to their problem in the form an overview of the curriculum and our teaching plans for the remainder of the project. This will insure that our plans address the attributes they desire in their new engineers.

Dissemination Plan

In addition to publishing our experiences teaching this course and the results of the design projects, we have several unique opportunities for engaging other universities in designing our curriculum.

Visiting Faculty. The Control and Dynamical Systems (CDS) department at Caltech, in which the umbrella courses and this project will reside, frequently hosts visiting faculty from a wide array of universities from both the United States and beyond. These faculty will participate in designing and teaching modules related to their areas of expertise. Recent visitors with an interest in engineering education include Jeff Shamma (Mechanical and Aerospace Engineering, UCLA) and Claire Tomlin (Aeronautics and Astronautics, Stanford). Our goal is to work with at least one visiting faculty member to develop a version of our curriculum for testing at their home institution in our second year of funding.

The CDS Alliance. Caltech has recently been awarded a grant by the Department of Education to establish the Control and Dynamical Systems (CDS) Alliance between the US and Brazil [13]. The CDS Alliance, whose current US members are Caltech, Princeton, and UC Santa Barbara, is developing a shared curriculum at leading educational institutions in the areas of Control and Dynamical Systems. These areas are well positioned to play a pivotal role over the next several years in shaping a common scientific language across a variety of disciplines, from mechanical, aerospace, and environmental engineering to bioengineering, communications, and economics. This wide range of applications makes these disciplines ideally suited for cross-disciplinary fertilization. A key focus of the activity is in developing new approaches to education and outreach for the dissemination of basic ideas to non-traditional audiences. The CDS Alliance will provide a mechanism to further develop course materials in this area and to disseminate those materials to a national and international collection of partner universities.

Project Personnel

Richard Murray is a Professor of Mechanical Engineering and the Chair of the Division of Engineering and Applied Science at the California Institute of Technology, Pasadena. Professor Murray's research is in the application of feedback and control to mechanical, information, and biological systems. Professor Murray has recently developed a new course at Caltech that is aimed at teaching the principles and tools of control to a broader audience of scientists and engineers, with particular emphasis on applications in biology and computer science. In addition, he was the primary faculty sponsor for Caltech's entry in the 2004 DARPA Grand Challenge.

Stephen Waydo received his B.S. in Aeronautics and Astronautics from the University of Washington in 2001 and is now a Ph.D. candidate in Control and Dynamical Systems at Caltech. His research interests include control of multi-agent systems, particularly with respect to verification of algorithms distributed across multiple mobile vehicles. He has participated as a teaching assistant in the design and implementation of Caltech's new control curriculum. His professional experience includes working at NASA's Jet Propulsion Laboratory in Mechanical, Propulsion, and Flight Systems Engineering. At Caltech he is supported by a Fannie and John Hertz Foundation Fellowship, and while at UW he was the recipient of a Mercury Seven Astronaut Scholarship.

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