The CDIO Capstone Course: An Innovation in Undergraduate Systems Engineering Education

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Abstract

In February 1999, the Department of Aeronautics and Astronautics at MIT initiated a new three-semester capstone laboratory and space systems design experience taught in the context of authentic engineering practice, *i.e.*, Conceive, Design, Implement, and Operate (CDIO). The objective of CDIO is to teach the basic concepts and disciplines of engineering in the context of hands-on exercises where students have the opportunity to manipulate concrete objects and ground abstract thought in experience. At the capstone level, a CDIO approach immerses students in all aspects of the lifecycle development of an engineering product, exposing them to important aspects of systems engineering not always experienced in conventional laboratory and design courses. A three-semester course sequence allowed students to develop a concept for a satellite formation flight laboratory for the International Space Station, build a high-fidelity prototype, and operate it for short periods of micro-gravity on NASA's KC-135. In addition, students experienced stages in the evolution of an aerospace product. This paper details this three-semester sequence, describes the project in the context of the learning experience, provides an assessment of the educational innovation, and suggests future modifications of the concept. The current capstone experience will also be described briefly. Overall, the first capstone experience was quite successful: a highly motivating project, a cohesive team of students, and a product that is being used nationally to advance space technology.

Introduction

Most engineering programs include senior design capstone courses because they provide opportunities for upper-level undergraduate students to apply what they have learned to real-world problems. [1-3] The MIT Department of Aeronautics and Astronautics has broadened the scope of a capstone design course to provide students with experiences in not only the design, but also the prototyping, testing, fabrication, and operation of a complex aerospace system. The CDIO Capstone Course is a component of major CDIO educational initiatives in the Department that include new teaching laboratories, a reformed curriculum, emphasis on active and experiential learning, and applications of technology for teaching, learning, and assessment.

The CDIO approach grew out of the need to provide students with more authentic learning experiences that would prepare them for the demands of current engineering practice and research. Most beginning engineering students, today, have had few prior experiences in building and repairing things, *e.g.*, cars or radios. They often lack the requisite foundation for understanding how hypotheses are formulated and tested without actually manipulating concrete objects. Students have difficulty learning engineering concepts and principles because they have no prior context on which to map new knowledge.[4-5] Concrete experiences in a laboratory can be instrumental in helping students accept new organizations of knowledge. Exercises based on genuine applications of knowledge build a rich and deep understanding of concepts. [6-7] Therefore, it is necessary to create for students an authentic context of activities and applications in which learning can occur.

In the process of reforming the aerospace engineering curriculum, we believed that we needed to develop a multi-year, team-based capstone design course with CDIO experiences. The department has two other required capstone courses. One is a two-semester laboratory course in which teams of two or three students conduct experimental research projects. The other is a design course in which groups of 15 to 25 students work together on a paper design of a large-scale complex aerospace system. They differ from the CDIO Capstone Course in that the laboratory course focuses on experimental research rather than the preparation of students for leadership in the CDIO of systems, and the design course stops with the conception and preliminary design of an aerospace system with no subsequent implementation or operation. The courses also differ in the number of students who comprise the teams. The CDIO Capstone Course replaces these two courses with a three-semester sequence that exposes students to a complete engineering lifecycle experience with hardware-related problems. Table 1 compares the curricular content of the conventional laboratory and design courses with the CDIO Capstone Course. *Italics* identify those curricular elements that are uniquely provided by the indicated course.

Table 1. Comparison of the Curriculum of the Laboratory and Systems Engineering Courses with the CDIO Capstone Course

Element of the Curriculum	Experimental Projects (laboratory course)	Space Systems Engineering	CDIO Capstone Course
Large Aerospace System Focus	**N/A** - Focuses on small scale projects	*Provides opportunity to conceive and design large-scale systems*	Reduced scale due to need to carry project through lifecycle
Experience with the research process	*Research hypothesis, design & test, comparison of data and models*	While not research, does expose students to data and model comparison	Focuses on comparison of models, design, and data analysis
Team environment, interface control, communication	**N/A** - Teams of two do not represent systems team environment	Team environment emphasized during design but interfaces are loose	*Strict interface definition and control*
Laboratory process, modeling and measurement	Emphasis on laboratory process, project planning, modeling and	**N/A** - The paper design is based solely on analysis	*Enhances laboratory experience with design iteration to meet requirements*

	measurement		*meet requirements*
Requirements, abstraction and trade analysis	**N/A** - experiment provides minimal experience with these processes	One of the fundamental curricular elements of this course	*Quantifiable requirements and constraints; feedback from other teams and from the design*
Individual responsibility, system integration, pushback	**N/A** - No integration of project into larger system	**N/A** - No hardware integration or pushback on requirements	*System integration enforces responsibility and requirements trades*
Verification and validation, carrier integration	**N/A** - No performance, functional or environmental testing	Minimal attention paid to this process in the form of documentation	*Qualification tests and carrier integration*
Subcontracting, procurement, mission operations	**N/A** - Only rare industry, carrier, or subcontractor involvement	**N/A** - No hardware or operations; documentation only	*Industry involvement, KC-135 operations, Shuttle integration*

The course also includes on-going formal training in many of the communication, interpersonal, and team skills necessary to carry out such a process. Instructors from the MIT Writing Program and the MIT Management School work collaboratively to design and teach the course.

The underlying philosophy of the CDIO Capstone Course is that submerging students into the complete lifecycle of an aerospace product over a substantial fraction of their undergraduate program gives them a better working knowledge of the elements of systems engineering than conventional laboratory and paper design experiences. By experiencing the full lifecycle, students gain a better appreciation for the ways decisions made early in the design impact downstream activities. For example, the design not only must focus on performance, but also must consider cost, manufacturing, testing, repair, operation, and safety.

A concerted effort was made to make the product something of value to the aerospace research community. First, such a product would allow the course to leverage research, as well as academic, resources. For example, the product could be a testbed that would support research activities once the course activities were complete. Such an arrangement would provide graduate students and staff, as well as funds, to support the product in development. In addition, faculty time spent teaching the course would not only meet academic requirements, but also permit faculty members to direct focused activities that support their research. Second, developing a valuable product that leverages research funds forces the product to be of high quality, often beyond students' initial expectations of their own achievements. Seeing concepts emerge into reality, particularly when the final product exceeds expectations, provides a dramatic boost to students' self-confidence. Furthermore, they have a concrete and successful experience that is the basis for future engineering endeavors.

A three-semester capstone experience serves four important purposes. First, students are provided with the time to make and learn from mistakes. If students are continuously guided toward correct decisions, they never have the opportunity to learn to *recognize* bad decisions, or more importantly, to *recover* from bad decisions. Second, the length of the project allows students to work through interpersonal conflicts, and as a result, develop and practice team skills with the confidence to assume responsibility to guide the development of the product. Third, students are exposed to various forms and iterations of technical communications. Conducting several reviews and writing multiple revisions of design documents for the same project allows students to build upon their work, strengthening both their design and their communication skills. Finally, the duration allows students to take the design to a higher level of quality than a conventional one- or two-semester course would allow. Since quality is an essential element of any aerospace product, this experience is invaluable to their careers.

The Research Project and Its Relation to the CDIO Capstone Course

The Air Force Research Laboratory funded an MIT project to develop a six-degrees-of-freedom micro-gravity testbed to evaluate formation flight control algorithms required for future separated spacecraft missions. This project, called SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites), required the development of a system of three autonomous nano-satellites. Each satellite needed self-contained propulsion, sensing, communications and control. While the satellites were designed for the International Space Station (ISS), students operated them on NASA's micro-gravity aircraft, the KC-135.

To facilitate the design of the hardware, teams of two students were assigned to the various sub-systems. Each team had a mentor who was either an MIT faculty member, staff member, graduate student, or an employee of Payload Systems Incorporated, an industry partner on the project. Where many partnerships with industry involve engineers who function as part-time advisors, the mentors from Payload Systems attended all lectures and lab sessions. In this way, the class was able to interact with industry representatives on an almost daily basis. In course evaluations, students reported that this interaction with mentors was one of the most valuable aspects of the project, and was made even more beneficial by the frequency of the interactions.

In addition to increased efficiency, the assignment of subsystems to small groups had two benefits. First, it empowered each pair of students, giving them complete control over an aspect of the project, increasing their personal investment in the overall project. Second, it gave students the experience of working in small teams. From the start, the MIT Aero/Astro program encourages collaboration and teamwork, and students come to realize that their classmates can be as great an educational resource as their teachers. Each team member brought different skills to the project, and team members were able to organize themselves and teach each other in order to accomplish their objectives. In addition, as deadlines approached, each person was acutely aware of his or her own responsibilities to the other person on the sub-system team and to the project as a whole. In each of the three semesters, four or five members of the class were asked to play dual roles in the project, one as a member of a subsystem team, and the second as a member of a systems engineering team. The latter team was responsible for documentation, scheduling and planning of operations, coordination of system integration, and the flow of information between the subsystems.

During the *Conceive-Design* semester, formation flight requirements and ISS constraints were defined and flowed down to subsystem specifications. Sub-system teams developed designs for propulsion, metrology, structures, power and avionics, and software and communications using modern computer-aided design tools in concert with bench-top prototypes and physics-based models. Progress was formally presented through three reviews (Requirements, Preliminary Design, and Non-Advocate Reviews) and a design document.

During the *Implement* semester, students made component make-buy decisions, acquired sub-system components, integrated these components into complete sub-systems, and tested their functionality to verify that they met requirements. Subsequently, these sub-systems were integrated into a prototype of the flight SPHERES. Testing was performed on the prototype to verify that system-level requirements were met. Lessons learned at the system and sub-system levels were translated into design modifications and formally documented in the design document. The updated design was presented at the Critical Design Review, attended by guests from industry and government, in preparation for flight hardware procurement that was initiated in the latter portion of the semester.

The final *Operate* semester started with flight hardware fabrication, verification, and acceptance. Planning for operations on NASA's KC-135 included development of operations timelines, integration and safety documentation, and packing and shipment procedures. Two KC-135 sessions were conducted. Half of the class flew in February while the other half flew in March. Each session consisted of students undergoing altitude chamber qualification, presenting a KC-135 safety briefing on their payload, and four days of flights where each flight consisted of 40 thirty-second parabolas. After each flight, the team debriefed the results, planned the following day's activities, and developed and verified the next day's flight software.

As mentioned previously, the CDIO Capstone Course was initiated as an alternative to existing capstone experiences. Thus, it was important that this new approach achieve at least as much as the alternative capstones. Specifically, the new capstone was designed so that students would be able to:

- apply their knowledge of underlying sciences and core engineering theories
- demonstrate reasoning ability and problem-solving skills
- model, estimate, and analyze alternative solutions to problems
- conceive a design from customer requirements by flowing down requirements and conducting design trades
- design the system by building and analyzing mathematical models as well as hardware prototypes
- implement design in high quality hardware by managing their sub-system interfaces, procuring parts from vendors, conducting acceptance tests, and performing system integration
- operate the system in qualification tests in the laboratory and in the field

- work successfully in teams
- communicate designs both in technical briefings and technical reports
- manage large-scale complex projects effectively
- demonstrate personal and professional skills and attitudes

In many ways, the CDIO Capstone Course surpassed other experiences in teaching important lessons that can be learned only in an authentic engineering environment. First and foremost, the course was based on the fundamentals of underlying sciences, core engineering theories, and engineering reasoning and problem solving skills. At the same time, the class maintained a hands-on structure that compelled students to learn on their own.

Early in the *Conceive-Design* phase, students had to learn to model, estimate, and qualitatively analyze the various pieces of the project, to pose hypotheses, and to define goals to be accomplished throughout the life of the project. During the *Implement* phase, the class focused on experimentation and knowledge gained through practice and discovery. It was here that more typical principles of research and inquiry were learned, from experimental design in the lab to archival inquiries and surveys found in existing documentation. Although much of the research program stepped into new territory, the class still had a budget cap, requiring that students devise ways to reach intended goals in the most efficient manner.

Students were also required to handle the documentation and defense of their subsystems. On several occasions, students were required to speak publicly about the SPHERES research program. In November 1999, students traveled to NASA Goddard Space Flight Center to participate in a safety mission briefing. Through various presentations throughout the project, students recognized the need for forming effective teams, learned important leadership skills, and improved their communications skills. Documentation led to effective written communication, and the use of computers in the classroom environment led to electronic and multimedia savvy that proved important in explaining the process to others.

The *Operations* phase was perhaps the most enjoyable for the students. Following the integration section of the design process, the operations structure allowed students to step back from their individual sub-systems to look at the project more holistically. Though an evolutionary process, SPHERES models moved into different prototype phases, resulting in a stable flight hardware model in time for the February flights. Operations management became an important issue at this time, as did teamwork and good communication.

Because communication and teamwork skills are important objectives to this capstone course, they were taught concurrently in a companion *Communications Practicum*. These skills included technical briefings and presentations, graphics, technical writing, team dynamics, conflict resolution, and colleague assessment. Presentations and reports were observed and critiqued by an instructional team led by a communications specialist from the School of Humanities and Social Sciences. Both the instructional staff and student peers rated team participation and team leadership skills.

On other levels, the CDIO Capstone Course taught important personal and professional skills that students will need when they enter the real world of industry, contracts, and acquisitions. The integration of different levels of industry and outside interaction taught students to show initiative, to persevere, and to be flexible. The length of time to complete project and learning objectives required a willingness to take risks, creativity, and critical thinking. On a personal level, the class gave back to students what they put into it. Professional behavior, integrity, responsibility, and accountability were expected at all times.

The CDIO Capstone Course incorporated pedagogical approaches based on a set of research-based learning principles.

- *Learning in a team environment* required the development of communication, presentation, listening, compromise, and consensus skills. [8-10] It also required that students develop business ethics that pertain to responsibility, attendance, delivering what is promised on time, and ensuring quality in the work. [11]
- *Learning in a laboratory environment* exposed students to the experimental iterative process where theory determines experimental design and the resulting data is used to refine the theory. This environment allowed students to develop an appreciation for error, uncertainty, and variability. Model validation enhanced confidence in model-based designs. [12]
- *Working closely with mentors, instructional staff, graduate students, and industrial engineers* provided unique views into the style, motivation, knowledge, experience, and perspectives of different engineering cultures. In this real-world situation, students learned that they could make substantial contributions without having complete knowledge of all aspects of the product. [13]
- *Employing mature design tools for mechanical and electrical design* gave students an appreciation for modern design capabilities. The experience allowed students to compare the strengths and limitations of simple analyses, tests, and computer-aided design results.
- *Conducting an evolutionary project* allowed the class to exercise the iterative design process and experience a greater ratio of final accomplishment to initial concept maturity and its consequent sense of achievement.

Assessment of the Educational Initiative

In order to determine the effectiveness and efficiency of the CDIO Capstone Course, we are examining student outcomes, student satisfaction with the learning experience, observations and judgment of the instructional staff, cost-effectiveness, and sustainability over time. Student outcomes are assessed at four levels: grades, team cohesion, product success, and external perspectives. Grades are perhaps the easiest to quantify but clearly do not represent the whole picture. Each student's grade was composed of five elements: classroom and laboratory participation, module development, colleague assessment, oral presentation, and written documentation. Participation was assessed by attendance, noting the degree to which the student facilitated productive team discussions, developing impressions of the student while mentoring their sub-system team, and reviewing mandatory laboratory notebooks. Module development refers to the development of physics-based and measurement-based models of their respective sub-system and using that model to make design decisions. Again, the individual sub-system mentors assessed these modules.

Colleague assessment was viewed as a very important part of the grade. Clearly in such a team project, the students are more responsible to each other than to the faculty. To formalize this responsibility, twice each semester students wrote constructive assessments of those students with whom they worked closely. If a particular student received few or poor assessments, the faculty were alerted to issues that needed to be resolved. Knowing that colleague assessments were due following major class events also alerted the students to their responsibility to support their fellow students during difficult times.

During oral presentations (formal and informal), the faculty and staff graded the speakers based on a set of pre-defined metrics. These included quality of verbal presentation, non-verbal presentation, answers to questions, clarity of message, and knowledge of audience. Written documentation consisted of the presentation viewgraphs and companion annotations, the requirements document, the design document, and the program plan. This set of grading elements comprehensively captured all aspects of the students' role in the course. Overall, the class average improved during the course of the three semesters as students became more enlightened as to their role in the larger project, as the design gained momentum, and as the students' enthusiasm increased.

Less quantitative were team cohesion, product success, and external perspectives. By the beginning of the third semester, the students essentially took over the high-level organization of the project. This was their initiative; it was not forced upon them. Clearly, they understood the big picture and were ready to assume programmatic responsibility. This could be achieved only by a team that was cohesive, interactive, and productive. Product success can be assessed by external demand. Subsequent to the class, the SPHERES facility has attracted funding for research from Lockheed-Martin and Draper Laboratory. Furthermore, DARPA's Orbital Express Program is funding SPHERES to be flown on the International Space Station in 2003 to help develop rendezvous and docking technologies for satellite servicing. In essence, the SPHERES facility developed by this class is now a unique, world-class research facility. External perspectives came from industrial and government representatives who attended reviews or heard about the course concept. Those who attended reviews provided very positive feedback and felt that since the students understood the issues well enough, they could be asked quite difficult and detailed questions. The most often expressed comment was the regret that such a class did not exist when they were undergraduates.

At the conclusion of each of the three semesters, students were asked about their satisfaction with the learning experience and about their own perceptions of having achieved the intended learning outcomes. In addition, at the end of the third semester, students were interviewed as a part of a video documentary of the SPHERES project. Sample excerpts from the video documentary illustrate students' enthusiasm.

> "When I first came to MIT, I had no clue that I would be doing anything as cool as this."
> "I never would have thought that I would be doing this!"
> "It has definitely been the culminating experience of MIT for me."

"This opportunity came up and it was just like, WOW, I want to do this."
"It's a completely different attitude to learning about aerospace engineering."
"It's given me a taste of the real world before I get the chance to get out there."

Some general trends emerged from the CDIO Capstone Course experience. First, students' attitudes towards the learning experience differed from other project-based courses. Students showed a greater sense of personal investment in the project. Some enjoyed the opportunity to apply their skills to a hands-on project. Others were excited by the sense of empowerment and responsibility that the project gave them. They were also drawn in by the prospect of operating their experiment in the unique aerospace environment available on board the KC-135.

Despite their enthusiasm, however, students felt that they spent more time working on the SPHERES project than they would have spent on other capstone design courses. In addition, several long lead items had to be addressed over the summer and during the Independent Activities Period (January), outside regular academic terms. Although the first few presentations required a great deal of preparation and organization, as the course progressed, presentations and documentation became easier to produce. Students seemed to enjoy communicating the project to the outside world more and more. They also became more confident in their dealings with suppliers, NASA centers, and other non-MIT entities. Representatives from industry and other outside organizations were impressed with both the scope of the project and the quality of its presentation.

One of the most interesting outcomes of the course was the group dynamic established among members of the class. Three semesters of working together, scrambling to meet deadlines, and traveling to Houston and other locations brought students close together. The shared experiences helped to establish a high level of trust, mutual respect, and camaraderie.

The CDIO Capstone Course required a considerable amount of effort on the part of the faculty. Fortunately, this effort not only directly supported the academic goals of the class but also supported the faculty member's research through the development of the class product. Several specific observations were made regarding this educational experiment:

- At least one good teaching assistant is instrumental to the success of the program.
- Staff members played strong roles in the sub-systems.
- All students took personal responsibility for the product.
- A few students had trouble working on open-ended problems.
- The students were very professional in their dealings with organizations outside of MIT
- Grading and formal feedback were less frequent than had originally been planned.
- Summer provided a time to tackle long-lead items.
- The final product exceeded everyone's expectations.

The course concept has four identified potential failure modes that need to be addressed. First, the project scope may exceed the capabilities of the class. A teaching assistant with very good laboratory skills is necessary to mitigate this problem, In addition, skill needs were identified in advance and subcontractor, graduate student and staff skills were drawn upon to fill in needed skills. The summer period between the first and second semesters was used to acquire long-lead items and de-scope options Finally, since the product was going to become a research testbed, research related tasks were delayed until after the class.

Second, the possibility that particular students do not deliver to their potential has a serious impact on the entire class. The best mitigation is motivation, responsibility, and not holding good students hostage to poor students. Mentors working closely with each sub-system helped faculty to distinguish between individual contributions and group deliverables. Colleague assessments conducted twice each semester emphasized that students had responsibilities towards their fellow students as well as to the faculty. As a last resort, the support staff could be drawn upon to fill in skill needs.

Third, as with all research programs, funding variabilities can threaten the health of a project. Therefore, cost budgets were tracked closely, financial support was diversified across several sources, and de-scope options were carried through the program. Fourth, in the event that a student cannot complete the three-semester sequence, he/she earns systems engineering credit for successful completion of the first semester.

Overall, the most exciting aspect of the SPHERES project has been the physical manifestation of the ideas developed over the duration of the course. The project was introduced as a set of functional requirements in February 1999, and a year later, we had fully integrated flight hardware. It was very exciting to observe the progress from concept to completed product.

Cost Effectiveness and Sustainability

The CDIO Capstone Course required a substantial resource commitment both in funding and faculty time. MIT's Department of Aeronautics and Astronautics supplied a $200K sub-contract to Payload Systems Incorporated, the industrial partner, as well as a teaching assistant. The Air Force Research Laboratory provided $200K for development of the SPHERES testbed in MIT's Space Systems Laboratory. NASA Goddard Space Flight Center funded two weeks of operations on the KC-135 micro-gravity aircraft. Overall, the funding supported staff salaries, hardware development, laboratory infrastructure, travel, and the KC-135 flights. The course also required a considerable amount of faculty time. Fortunately, faculty time supported not only the academic goals of the course, but also faculty research through development of the product.

Sustainability of this type of learning experience, given its scale and associated funding, is an important concern. There is no guarantee that such large-scale research projects will be available on a regular basis for undergraduate capstone experiences. Fortunately, this concern was addressed by coupling the project with the experimental research program being conducted within the Space Systems Laboratory at MIT. This allowed the project to tie strongly to the research side of the Department thereby providing motivating, cutting-edge projects; augmented funding; as well as stronger collaboration with faculty, staff and graduate students. An important benefit of strong collaboration with research activities and working with graduate students is that undergraduates better appreciate the context of their work and can make more informed decisions with respect to pursuing advanced degrees and prospective employers. Faculty satisfy not only their teaching requirement but also advance their experimental research program while subsidizing their research with a larger labor force, Departmental support, and extended exposure to the capabilities of potential graduate students. What has been learned as a result of this experience is that undergraduates are capable and highly motivated partners in research projects and in the conception, design, implementation, and operation of complex aerospace systems.

Conclusions

The CDIO capstone innovation represented one of the first efforts of the Department of Aeronautics and Astronautics to develop an aerospace product from concept to operation in the field with a group of undergraduates working within the framework of a formal course. The innovation had some clear successes. Team interaction clearly evolved from a faculty-led to a student-led program, showing that students developed a sense of leadership, responsibility, and ownership for the project. The final product exceeded the initial expectations of the students, has advanced the research program in the Space Systems Laboratory, and has attracted government funding for advanced development and operation on the International Space Station.

As expected, however, there are a few concerns. Some students had difficulty working in this open environment. Sustainability, in terms of new projects, continued funding, and continued faculty and staff energy is, at present, uncertain. Adoption of a project that turns out to be beyond the resources of the class would be problematic, both for the research project and for the students' achievement of the intended learning outcomes. Therefore, care will have to be taken to plan for the possibility of reducing the project's scope, and to distinguish course learning objectives from project objectives as much as possible. Continued refinement of the capstone experience will provide insight into these issues.

A second sequence of the CDIO Capstone Course was initiated in Spring 2001. The goal of the project is to demonstrate the feasibility of exploiting modularity in optical systems with modularity in spacecraft sub-systems to develop new methods for fabrication, deployment, and repair. The design-build experience will be sued to identify the size of optical systems beyond which modularity is more cost effective than monolithic systems. The students are building a prototype of such a system with almost all of the functionality of a real satellite. Since an actual launch is unavailable, the students are mounting the satellite on an air bearing, and will steer it to image the International Space Station as it crosses the sky. This second capstone experience will provide additional data for assessing the CDIO approach to curriculum and pedagogy. The framework of the course and the instructional staff are essentially the same as before, but the research project, product, industrial partners and some funding sources are new.

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