Enhancing Undergraduate Education in Aerospace Engineering and Planetary Sciences at MIT through the Development of a Cubesat Mission

Enhancing undergraduate education in aerospace engineering and planetary sciences at MIT through the development of a CubeSat mission

Matthew W. Smith[a], David W. Miller[a], Sara Seager[b]

[a]Department of Aeronautics and Astronautics
[b]Department of Physics and Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139

ABSTRACT

CubeSats are a class of nanosatellites that conform to a standardized 10 cm × 10 cm × 10 cm, 1 kg form factor. This miniaturization, along with a standardized deployment device for launch vehicles, allows CubeSats to be launched at low cost by sharing the trip to orbit with other spacecraft. Part of the original motivation for the CubeSat platform was also to allow university students to participate more easily in space technology development and to gain hands-on experience with flight hardware. The Department of Aeronautics and Astronautics along with the Department of Earth, Atmospheric, and Planetary Studies (EAPS) at the Massachusetts Institute of Technology (MIT) recently completed a three semester-long course that uses the development of a CubeSat-based science mission as its core teaching method. Serving as the capstone academic experience for undergraduates, the goal of this class is to design and build a CubeSat spacecraft that serves a relevant science function, such as the detection of exoplanets transiting nearby stars. This project-based approach gives students essential first hand insights into the challenges of balancing science requirements and engineering design. Students are organized into subsystem-specific teams that refine and negotiate requirements, explore the design trade space, perform modeling and simulation, manage interfaces, test subsystems, and finally integrate prototypes and flight hardware. In this work we outline the heritage of capstone design/build classes at MIT, describe the class format in greater detail, and give results on the ability to meet learning objectives using this pedagogical approach.

Keywords: CubeSat, nanosatellite, higher education, capstone class, conceive-design-implement-operate (CDIO).

1. INTRODUCTION

High-impact science, technology, engineering and mathematics (STEM) education programs typically require an element of hands-on learning. Such interactive activities serve to solidify fundamental concepts and demonstrate to students the real-world applicability of the technical subjects they are learning. At the undergraduate level, this often takes the form of courses in which students design and build a working prototype. This approach was pioneered in the Massachusetts Institute of Technology (MIT) Department of Aeronautics & Astronautics and is discussed in greater detail below.

The CubeSat standard was developed at Stanford University as a means of enhancing aerospace education through spacecraft that can be developed in an academic setting.[1] Combined with Poly-Picosatellite Orbital Deployer (P-POD)[2] for low cost piggyback launch opportunities, CubeSats allow users in academia—and increasingly government and industry—to access space via unified standards,[3] commercial-off-the-shelf (COTS) components, and a strong developer community. Over 30 CubeSats have been launched since 2003.[4]

This work describes a recent CubeSat-based undergraduate capstone course conducted at MIT. The course was the most recent in a series of highly successful Conceive-Design-Implement-Operate (CDIO) classes executed

Further author information: (Send correspondence to M. Smith)
M. Smith: m_smith@mit.edu
D. Miller: millerd@mit.edu
S. Seager: seager@mit.edu

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by the MIT Aero/Astro department over the past decade (see Section 2). The core subject matter of the course was ExoplanetSat spacecraft: a nanosatellite space telescope designed to detect transiting exoplanets around nearby bright stars. The ExoplanetSat project is a joint effort by MIT and Draper Laboratory, and students in the class matured elements of the design with guidance from MIT faculty, graduate student mentors, and experts at Draper. ExoplanetSat is a 3U CubeSat (10 cm × 10 cm × 30 cm, 4 kg) and will observe a single target star from low-Earth orbit (LEO). By precisely measuring the time-varying photometric signal of the target with sufficient precision, the satellite will attempt to detect transiting exoplanets. ExoplanetSat uses an single lens reflex (SLR) camera lens as its optical payload and COTS reaction wheel attitude control system for three-axis pointing stability. See Smith et al.[5] for additional details on the science case, requirements, and spacecraft design.

2. BACKGROUND ON CDIO

In the 1980s and 1990s, industry and academic leaders began to discuss the state of engineering education at the undergraduate level and identify desired attributes of engineers. An MIT team, led by then-Aeronautics and Astronautics Department Head Prof. Edward Crawley, conducted an extensive series of focus groups that included faculty, current students, industry leaders, and senior academics from other universities.[6] Their work uncovered a desired set of foundational qualities a graduating engineer should possess-qualities such as design skill, teamwork, leadership, and communications. Specifically, they found a critical need for engineers who could "conceive, design, implement, and operate complex, value-added engineering products, processes and systems in a modern, team-based environment".[7] Within the context of aerospace engineering one can ask the related question of, is there an accelerated way for students to gain real aerospace engineering experience, incorporating "best practices" with low programmatic risk? These questions motivated Crawley and his team to formulate the Conceive-Design-Implement-Operate (CDIO) approach to undergraduate STEM education.[6] Since its inception at MIT, use of the CDIO curriculum has grown; over 20 institutions worldwide are now part of the CDIO Initiative.[7]

In the CDIO paradigm, students participate in a space engineering program where they learn space by doing space. The "learn by doing" theme centers on student-built, student-managed, faculty-supervised satellite projects. CDIO involves students throughout the space project life cycle, encouraging them to think beyond disciplinary boundaries and to consider project needs in all phases. The aim is to create a highly engaging, real-world engineering experience that reinforces STEM educational goals in a dynamic and hands-on academic setting. CDIO creates dual-impact learning experiences where technical development is coupled with a modern team-based environment that stresses engineering leadership, collaboration, and communication. This simultaneously promotes learning of technical fundamentals (e.g. teamwork) and practical skill sets (e.g. spacecraft design).[7] The benefit is a richer STEM experience that actively engages students in a cutting-edge real world project, preparing them for later success as aerospace professionals. The MIT Aero/Astro Department pioneered this CDIO methodology[8] and has executed six highly successful CDIO courses over the past decade.

2.1 Bridging the engineering/science divide

Design/build classes at MIT and elsewhere are effective at exposing students to the challenges of interfacing various spacecraft subsystems. However, a challenging and often overlooked element is the interface between scientists and engineers. Tradition holds that the scientist sets the mission objective and the engineer then designs the spacecraft to meet that objective, with the two individuals having limited interaction as the project matures. The scientist had minimal engineering training and the engineer usually does not fully understand the nature of the science. The scientists and engineers operate independently, and neither group fully understands the details and implications of the work of the other group

This divide can threaten the success of space missions, hence it is imperative to train the next generation of scientists and engineers to collaborate throughout the project life cycle. The ExoplanetSat CDIO course accomplishes this by opening enrollment to students in the Earth, Atmospheric, and Planetary Sciences (EAPS) and Physics departments. Roughly one sixth of the students in the fall semester were either from these departments or had a science focus. Furthermore, there is a dedicated science faculty member (Prof. Seager) on the teaching staff. ExoplanetSat is a science-driven mission, therefore the students were forced to negotiate tradeoffs between science and engineering requirements from the very start of the design effort.

2.2 Past CDIO classes at MIT

Roughly 10 years of experience in the planning and execution of CDIO capstone classes at MIT preceded the ExoplanetSat course. Past projects have included legged rovers (MoRETA), high-ΔV orbital transfer vehicles (MOTV), sparse aperture optics (ARGOS), and propellant-less propulsion (EMFF) (see Figure 1).

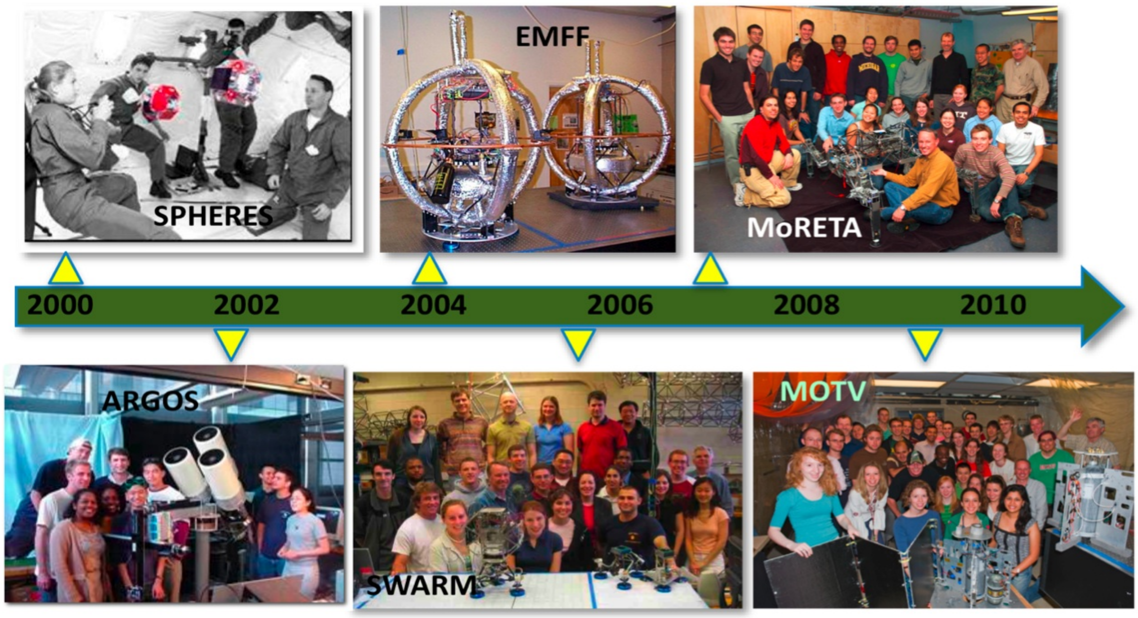

Figure 1. Past CDIO capstone classes conducted in the Department of Aeronautics and Astronautics at MIT.

The first CDIO capstone course ever taught was development of the Synchronized, Position, Hold, Engage, Reorient, Experimental Satellites (SPHERES) prototypes.[9] SPHERES is a free-flying test bed for testing satellite formation flight algorithms in 6 degrees of freedom. Students in this pioneering course designed and built the spacecraft prototypes and tested them on NASA's KC-135 parabolic flight aircraft (Figure 2a). A decade later, SPHERES is now a fully operational facility on the International Space Station (ISS),[10] demonstrating that CDIO-derived projects can have an impact at the national level (Figure 2b).

(a) (b)

Figure 2. (a) SPHERES prototype testing on NASA's KC-135 aircraft by members of the first CDIO capstone course and (b) SPHERES operational facility currently aboard the ISS.

3. COURSE DETAILS

Each CDIO class takes place over three semesters, beginning in the spring of junior year. The first semester is devoted to concept generation, requirements definition, and initial design. The second and third semesters, taking place during senior year, focus on design refinement, hands-on laboratory work, assembly, integration, and test. The first semester of the most recent sequence took place during the spring of 2010 and results for the sequence are discussed below. The goals for the three-semester sequence are as follows:

- Present complete designs for the satellite which fulfills all mission requirements and is within the given constraints.
- Design and build, throughout the three semesters, a spacecraft that accomplishes all mission objectives
- Enhance students' abilities for the *build* phase by providing hands-on experience through labs in earlier phases.

3.1 Organization

On average, 40 to 60 students take the CDIO capstone class and a similar number enrolled in the CubeSat-based course described here. The students begin with a customer mission statement (i.e. the science case), flow down requirements, conduct trades, develop the design, fabricate prototypes, and test them in an operationally realistic environment. In parallel, they document their design, conduct major design reviews, interface with customers and reviewers, and experience the other aspects of working in a project team environment.

In order to allow for detailed subsystem design and to reflect organizational structures common in industry, students in the course were grouped into the following subsystem teams. While the teams are formally separate, active interaction between students is required to work effectively. Indeed, teaching effective cross-disciplinary communications is a primary objective of the CDIO approach. The student teams are as follows:

- Science / Payload
- Attitude Control Subsystem (ACS) / Guidance, Navigation, and Control (GNC)
- Structures, Mechanisms, and Thermal
- Power
- Avionics and Software
- Communications
- Systems

Lectures relevant to system-wide concepts (e.g. requirements definition, testing, safety, etc.) and specific subsystems will occur during lectures near the start of the first semester. As the semester continues, class time is increasingly devoted to intensive, hands-on design work by the subsystem teams. A network of MIT faculty, technical staff, graduate students, and external subject matter experts serve as mentors to advise the students as the move through the design process. Table 1 shows a listing of the mentors.

Since leadership is a key skill in engineering design work, students will transition into leadership roles. The faculty and staff continue to be available throughout this semester as well as subsequent semesters as mentors. As the semester progresses, the class format transitions from instructor-led lectures to assistance and problem solving during student-led work sessions.

Table 1. Mentor areas of expertise.

Mentor	Position	Structures	Power	Thermal	Communications	ACS/GNC	Science/payload	Avionics	Systems	Space qualification
David W. Miller	Professor	✓				✓	✓		✓	
Sara Seager	Professor						✓			
John Keesee	Senior lecturer				✓				✓	✓
Alvar Saenz-Otero	Research scientist		✓		✓	✓		✓		
Javier de Luis	Industry mentor								✓	✓
Paulo Lozano	Professor		✓							
Paul Bauer	Research specialist	✓	✓					✓		
Matthew Smith	Teaching Assistant	✓					✓		✓	
Christopher Pong	Teaching Assistant					✓				
Alessandra Babuscia	Teaching Assistant				✓					
Ryan McLinko	Teaching Assistant	✓							✓	
George Sondecker	Teaching Assistant	✓		✓						
Corey Crowell	Teaching Assistant					✓				
Matthew McCormack	Teaching Assistant		✓		✓			✓	✓	

3.2 Lectures, laboratories, and work sessions

MIT's system for course load accounting is based on hour-long units of student work. The CDIO capstone class is a twelve unit course. Four hours are formally scheduled twice a week. At the beginning of the semester, this formal class time is divided between instructor-led lectures (0-2 hours/week, see topics below) with the remaining time (2-4 hours/week) scheduled for students to work with their design teams. The remaining 6-8 hours/week are to be scheduled by students for independent and team activities. During the third semester of the sequence, units are devoted almost entirely to laboratory work and formal reviews.

The lecture element of the course is concentrated toward the beginning of the first semester in order to acquaint students with the project and address specialized technical topics they may not have encountered in prior classes (e.g. optics, environmental control and life support, the space qualification process, etc). Additional early lecture topics include requirements flowdown, project management, and communications. The last item is led by a staff of experts on technical writing and communication in an engineering setting. The communications instruction is a key element of the CDIO syllabus, as skill in communication is a highly sought-after trait in engineering leaders.

In addition to lectures, students attend skill development laboratory exercises during the first semester (see Figure 3). These labs are aligned with the five spacecraft subsystem teams (systems does not have its own lab). The purpose of the labs is to provide hands-on skills early in the design process so that this experience can be incorporated into each team's designs. The experience should also enhance the ability of the students to make critical design decisions and begin manufacturing of spacecraft components early in the second semester. Teams design, build and test an experiment and interpret the results in terms of their theoretical models. Two laboratory bench reviews occur near the end of each semester. During these reviews, students demonstrate their laboratory experiments, present analysis and results, and field questions from the teaching staff.

Figure 3. Students working on avionics hardware during a skills development lab.

Finally, group work sessions occur during the class time starting from the first week of the semester. They consume more of the available time as lectures are phased out. These sessions began with an all-hands project meeting wherein each team gave status updates and asked relevant questions of the other teams. Because the ExoplanetSat exhibits very tight coupling between the subsystems (due to mass, volume, and power constraints), these sessions were very helpful in revealing subsystem interactions that could be problematic in later phases of the project. Following the all-hands meeting, the subsystem teams would then work on individual issues, consulting with other teams as needed. Group work would take place primarily in a single room, facilitating rapid person-to-person interaction and design maturation in a manner similar to that in modern "concurrent engineering" environments[11] (see Figure 4).

(a) (b)

Figure 4. Student-led group work session: (a) students from multiple subsystem teams mature the structural design and component layout in real time, (b) additional student interaction to close the component layout.

In the third semester, the focus of activity focuses to implementation of an engineering version of the spacecraft. This engineering model is intended to capture the functional characteristics of the flight vehicle, without an expectation of surviving environmental qualification testing (e.g. launch vibe, thermal vacuum, etc). For the ExoplanetSat project, engineering models were created at the subsystem level. This included a structural engineering model to evaluate manufacturing and assembly techniques (Figure 5), and a functional "flat-sat" bench top version of the power subsystem.

Figure 5. Students building an engineering model of the structural subsystem. The structural engineering model is used to evaluate manufacturing techniques, fastening methods, and fixtures for internal components.

3.3 Deliverables

Students are expected to deliver a number of written and oral accounts of their work on the project. These deliverables serve both as a means of evaluating student performance (see Section 3.4) and document the design for later semesters.

3.3.1 Design document

The satellite team produces a design document at the end of the semester. The design document is a coherent merger of all the team members' portfolios. Each design document captures the organization, requirements, trades, design, budgets, and test results of the project. These are evaluated for technical content and communications skills at the team level. This document should combine the results of all subsystem work. This means that each team's design document should present a design which has substantial detail on a spacecraft which accomplishes all given requirements. The design document also incorporates prototype development results that support the subsystem designs. The final design documents will incorporate the changes in design that occurred after the initial design document submittal, any recommended changes given by faculty/mentors, and a complete integration and test plan for the satellite design document.

3.3.2 Portfolios

The portfolio is an ongoing, continuously expanding and revised document which is a portion of the final design document. The portfolio shows the individual work of each student as a contribution to the larger project. It combines both "spacecraft" work and laboratory work. The portfolio should show congruency between the student's tasks. It is ideal to use the portfolios as both a statement of current design progress but also as a draft of future sections of the design document. The portfolio is not a lab notebook, but rather a concise summation of information in a lab notebook. Portfolio submissions occur periodically during each semester and are evaluated for both technical content and writing skills.

3.3.3 Formal reviews

During the first semester of the capstone course there are three formal reviews: System Requirements Review (SRR), Conceptual Design Review (CoDR), and Preliminary Design Review (PDR). These reviews expose students to an environment similar to that of real-world aerospace projects. They also serve as a means of documenting progress and improving presentation skills. Over the duration of the three formal reviews, each team member will present for approximately 10 minutes. Each review consists of two parts: a technical review (on the current status of the design) and a management review (on the current system level status), lasting one hour per satellite team. Reviews are be evaluated by the course instructors and outside experts for technical content and communications skills.

Figure 6. Formal review in progress.

3.4 Learning objectives

Below are detailed learning objectives (LO) and measurable outcomes (MO) for the capstone sequence. Measurable outcomes are the means by which learning objectives are graded.

At the completion of the first semester students will be able to,

LO 1: Summarize the mission requirements and develop a set of system and sub-system requirements that define a vehicle that meets the mission requirements.
- **MO 1.1:** Requirements analysis in Design Document
- **MO 1.2:** System Requirements Review (SRR)

LO 2: Develop a set of Figures of Merit (FOM) that quantitatively characterize the performance for the system to meet the mission requirements.
- **MO 2.1:** Conceptual Design section of Design Document
- **MO 2.2:** SRR

LO 3: Develop a system architecture which provides a "best solution" to meet the mission requirements based on the FOM.

MO 3.1: Conceptual Design section of Design Document
MO 3.2: Conceptual Design Review (CoDR)
LO 4: Based upon the chosen system architecture, design a vehicle which "closes" technically, i.e. satisfies the laws of nature; is build-able within the time and cost constraints; can be tested to verify that it meets the mission requirements; and is operable in the mission environment.
MO 4.1: Preliminary Design Review (PDR)
MO 4.2: Conceptual and Preliminary Design sections of Design Document
MO 4.3: Report of lessons learned from previous experiences

At the completion of the third semester students will be able to,

LO 5: Compile the detailed vehicle design with analysis and drawings to a level such that the vehicle could be produced by someone else.
MO 5.1: Critical Design section of the Design Document
MO 5.2: Critical Design Review (CDR)
LO 6: Fabricate or acquire subsystems and assemble the complete system in preparation for testing and evaluation.
MO 6.1: Manufacturing and Testing Plan sections of Design Document
MO 6.2: Acceptance Review (AR)
LO 7: Execute system and subsystem level test to demonstrate that the vehicle can be operated safely and achieve the mission requirements.
MO 7.1: Bench tests, system tests, environmental tests.
MO 7.2: Execute the mission
LO 8: Report the outcomes of the vehicle performance and resulting lessons learned.
MO 8.1: Post Mission Review
MO 8.2: Lessons learned document

Throughout all three semesters students shall,

LO 9: Apply project management methods to execute the project on schedule, with resource constraints, and to deliver the technical performance measured by the FOM.
MO 9.1: Management Summary section of the Design Document
MO 9.2: Project reviews (SRR, CoDR, PDR in the first semester; CDR, AR in second/third semesters)
MO 9.3: Risk management
LO 10: Keep records of work done and document progress made to achieve the design project objectives.
MO 10.1: Meeting notes, notebooks, action item list
MO 10.2: Portfolios
LO 11: Communicate facts, findings, and ideas to peers, supervisors, and mentors.
MO 11.1: Formal reviews
MO 11.2: Design Document
MO 11.3: Portfolios
MO 11.2: Informal documents on file sharing system
LO 12: Evaluate progress toward team and class goals.
MO 12.1: Self-assessment
MO 12.2: Peer reviews

3.5 Infrastructure

A robust computing infrastructure greatly enhances the work output possible during the capstone class. The ExoplanetSat course uses a server-based fileshare running Apache Subversion. This provides a unified location for all project-related files to be stored and organized. The subversion revision control system ensures proper configuration management throughout the course. Students access the fileshare either through a web interface or shell-based applications (e.g. TortoiseSVN).

In addition to the fileshare, several mailing lists are used for communication from mentors to students, and between students. There is a students list consisting of enrolled students and teaching assistants (no faculty), a faculty list, and teaching assistant list. There are also separate lists for each of the subsystems and a list for the team leads.

A variety of computer-based analysis packages also facilitate student design work. Matlab and Simulink are used as a general modeling environment and are particularly useful for the ACS/GNC team. Structural analysis is accomplished via NASTRAN, while SolidWorks is used for structural design; the related COSMOSWorks application is used for additional analysis. Satellite Tool Kit (STK) is used for communications and target star coverage analysis.

Laboratory and testing facilities at the MIT Space Systems Laboratory (SSL) and elsewhere at the Institute provide students with unique opportunities to develop and evaluate their hardware. The Gelb Machine Shop in the Aero/Astro department serves as the main fabrication facility, with several computer numerically controlled (CNC) mills and lathes, and an OMAX precision abrasive water jet system. The SSL houses an electronics development facility, numerous dynamics and controls test beds, a clean room, and avionics and communications test facilities. Space qualification testing occurs at Lincoln Laboratory, which has a shake table for vibration testing, a thermal vacuum chamber, and an anechoic chamber.

4. RESULTS

Students successfully completed a preliminary design of the ExoplanetSat spacecraft and matured many of the critical subsystems to the level of an engineering unit. Figure 7 shows the final semester students, teaching assistants, and faculty in the SSL with the structural engineering model.

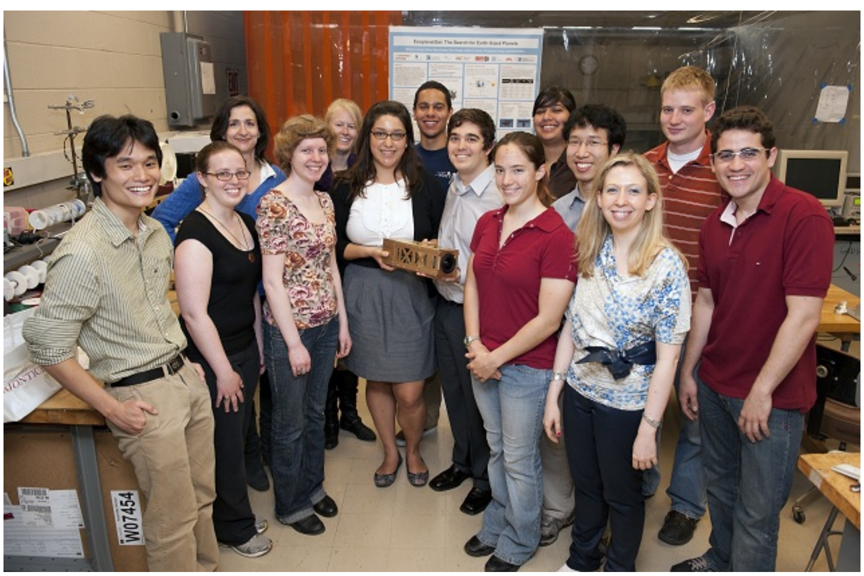

Figure 7. Class participants in the SSL with the ExoplanetSat structural engineering unit.

A primary result from the first semester of the ExoplanetSat CDIO capstone course was insight into the challenges and benefits of combining science and engineering students into a single class. At the beginning of the semester, it became obvious that the two groups spoke a different "language" when describing their requirements, constraints, and performance targets. For example, requirements on the science subsystem would occasionally drive unreasonable engineering requirements. Students were forced to negotiate competing elements of the design. This was exacerbated by the fact that available mass, volume, and power were severely constrained, thus decisions on spacecraft subsystem design are highly coupled. The all-hands meetings and question/answer sessions at the start of each group work session were effective in addressing this. The entire group could hear about the challenges that a given subsystem team encountered and could ensure in real time that proposed solutions did not have unanticipated detrimental cascading effects in other subsystems.

5. CONCLUSION

The aim this and other CDIO capstone classes is to realize a program that is educationally effective and more exciting to students. The aim is to simultaneously nurture proficiency in technical skills and non-technical (but still vital) collaborative skills. CubeSats are an suitable means of achieving the CDIO goals, as they offer hands-on experience and low-cost launch opportunities.

5.1 Lessons learned

Below are lessons learned from this and previous MIT CDIO capstone classes. They were gained through hard work and experience, representing the combined knowledge and suggestions of hundreds of students. Students should be encouraged to read the lessons learned prior to the start of each semester. By understanding the cause, effect, and solution to common problems, the class will be able to work more productively, which leads to a better product and learning experience.

- Students often get into the mindset that they cannot perform their work until they get information from others. This inevitably leads to a drawn out, sequential process that consumes precious time. It is important to search for tasks that can be done concurrently or on a "first pass" using preliminary estimates. Once the needed information becomes available, utilize it to complete your work. This is especially true with regard to the first portfolio submission.
- Students should lead through example, not orders. Sometimes the quietest person can be the best leader. The person who identifies and solves problems, and helps others to do the same, is a natural leader.
- Students should seek multiple views and opinions on questions. Unlike standard homework problems, design choices have many possibilities. It is often hard for a single individual to think of multiple approaches. This is where the team approach becomes valuable. Always take a moment to consider opposing arguments during discussions. Often trying to actually argue in favor of the opposition will help provide a new perspective which leads to a better design. Avoid rejecting suggestions "out of hand" without pausing to reflect. Often "one thing leads to another" and positively thinking about a suggestion will lead to yet a new idea.
- Designing, building and operating a product requires a working appreciation for hardware fabrication and testing techniques. Students should acquire this experience as early in the program as possible. A spiral approach is effective whereby the team goes through a complete cycle, knowing it does not yet have the final design or answer, but in the process gaining valuable experience.
- Unlike classes with tests and problem sets that provide weekly updates on performance, this class is more open-ended and representative of the "real world." Students should learn to self assess. They must develop the skills to recognize when they are doing well and when their performance is sub-par. They should ask themselves, do teammates look to them for guidance? Are they on time with deliverables and attend all scheduled meetings, both inside and outside of class? Are they a major contributor during "crunch times"? Has the class started to pass them by?
- Students are often unable to connect previous classes on fundamental subjects (e.g. physics, thermodynamics, structural mechanics) to the project. It is suggested that students be provided incremental assignments that ask them to explicitly link what they have learned to a problem that they are facing on the project. Such assignments should take place early in the sequence (i.e. first semester), with mentors and faculty reinforcing links between theory and practice during subsequent semesters.

5.2 Future work

The CDIO capstone class described here will continue in future years with new spacecraft projects. MIT was recently awarded the student contribution to the OSIRIS-REx asteroid sample return mission. The class beginning in Fall 2011 will focus on the development of an X-ray spectrometer for the mission.

Work will also continue to refine the execution of the class. For example, the fileshare is very useful for document storage and configuration management, however it is prone to malfunction when different platforms (i.e. Windows vs. Macintosh OS) and tools (i.e. internet browsers vs. shell applications) are used to access it. Other options, such as a course wiki, have been used in the past therefore a hybrid solution to document storage and tracking might be necessary. Finally, given the success in combining science and engineering students this term, and the importance of doing so from an educational standpoint, the authors will endeavor to strengthen connections between science and aerospace engineering in future classes.

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