Space Systems Engineering in Undergraduate Education

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Abstract

Engineering design for harsh constraints such as those faced in space environments provides a unique means for students to experience real-world design. An experiential learning course designed to introduce undergraduate students to the space sciences, engineering design with harsh constraints, and active learning through critique of technical literature and fieldwork is discussed. The University of Tennessee at Chattanooga's electrical engineering course, Embedded Systems for Space Applications, provides a means for students to learn difficult topics through deliberate practice and mentorship from graduate researchers and faculty. Two primary learning methods are utilized: hands-on learning through the design, prototyping, and development of a nanosatellite or high-altitude balloon payload, and student-driven review and critique of technical literature. Local community and K-12 partnerships broaden the impacts of the effort by providing outreach and collaborative opportunities in addition to the dissemination of student-designed product for enhancing education in the space sciences.

Keywords

Design Thinking, Electrical Engineering, Experiential Learning, Project-Based Learning, Space Systems

Introduction

The increased use of the small satellite system (CubeSat) for advancing space science missions has improved the exposure of undergraduate students to engineering for space systems by providing opportunities beyond proof-of-concept demonstrations. Since their introduction in 1999, CubeSats have been increasingly utilized for Earth imaging and science missions beyond their historical use as demonstration and education vehicles[1]. While various successful University-level programs are focused on the research and development of CubeSats, there are few that integrate skills learning that is typical in undergraduate electronics education and application in complex system design required for CubeSat development[2]. Moreover, the constraints imposed by the space environment (*i.e.*, temperature extremes, radiation, vacuum) are often outside of the typical operating specifications of commercial devices. Consequently, students are not often exposed the typical operational requirements of space systems prior to experience in a research laboratory, graduate-level or post-baccalaureate work environments.

Project-based learning (PBL) is a pedagogy that uses a dynamic, hands-on approach in the classroom that has been cited to help students master critical skills essential for college and career readiness[3]. Students in PBL have demonstrated improved problem-solving skills when compared to more traditional classes and are able to apply what they learned in other contexts[4]. PBL students in mathematics and science also show enriched critical thinking abilities[4-7]. This paper describes the implementation of PBL in an undergraduate electrical engineering course on space systems engineering, ENEE 4999: Embedded Systems for Space Applications (ESSA). The course is a designated as an experiential learning course at the University of Tennessee at Chattanooga (UTC) in support of a university-wide initiative (ThinkAchieve: Beyond the Classroom) to encourage student participation in and reflection on experience-based learning[8]. The course is designed to encourage the deliberate practice of engineering and computer science principles through the design, prototyping, and development of a CubeSat or high-altitude balloon (HAB) payload. Students are eligible to take the course after completing a course in embedded systems, field-programmable gate arrays, or microprocessors. Two primary learning methods are utilized: hands-on learning, and student-driven review and critique of technical literature (journal club). Traditional in-class lectures are not utilized; rather, an inquisitive-based, dynamic approach is employed that allows the students to, in part, decide on the topics to explore. Ideally, the content discussed throughout the course is beneficial to the realization of the students' payloads. The following sections describe the technology used as a framework for the student projects, the details of the course, and assessment of the first two offerings conducting in the spring semesters of 2016 and 2017.

CubeSat Small Satellite Framework

Small satellite spacecraft have a mass less than or equal to 500 kg[9]. The CubeSat is one such small satellite standard that was developed by California Polytechnic State University and Stanford University in 1999 and can be classified as a nanosatellite or picosatellite ranging in mass from just under 1 kg to over 12 kg. The standard 10x10x10 cm^3 CubeSat weighs no more than 1 kg and is termed the "one unit" or 1U. CubeSats may be developed in 1U increments[10]. Due to size and weight limitations, CubeSats present some unique challenges when compared to conventional large-scale systems, including the need for innovative propulsion and attitude control systems, small-scale electronics robust enough for the harsh space environment, reliable, small-scale and innovative communication systems, and conservative power management[9]. Recent advances have allowed the CubeSat to become a viable spacecraft for conducting science missions and have seen an increase in use by commercial, government, and military sectors (Figure 1) [11]. The primary advantage of the system is the relatively low cost and quick development-launch cycle when compared to standard spacecraft development. As such, the CubeSat has become a popular spacecraft for commercial low-Earth orbit missions and represents an excellent framework for a tangible learning experience in spacecraft design.

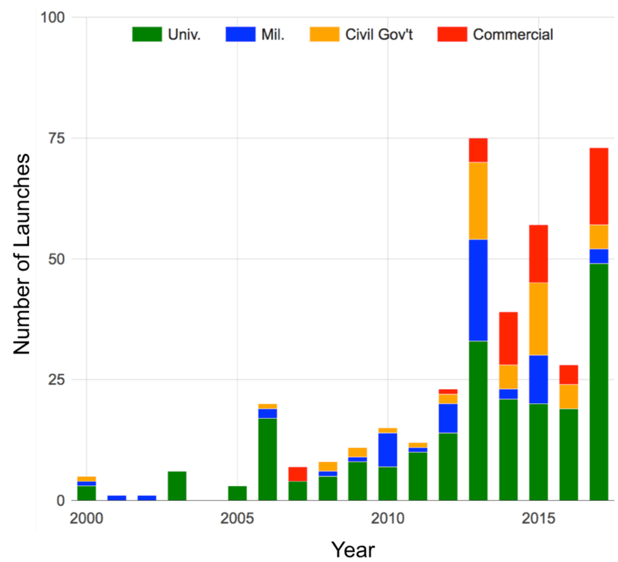
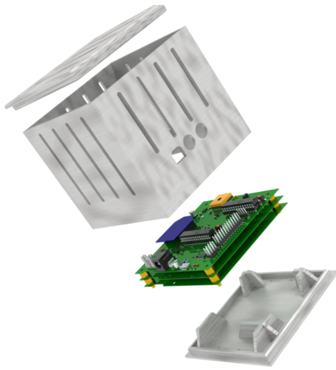
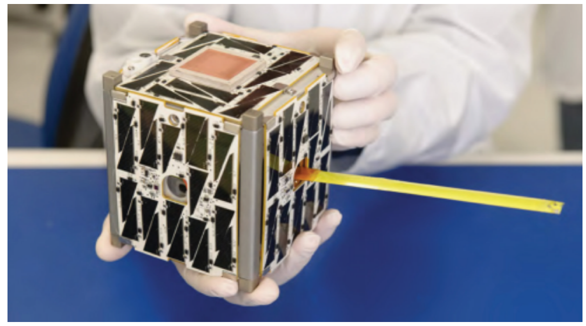


Figure 1. CubeSat launches versus year since 2000. Launches are color-coded by mission type: University (Univ.), Military (Mil.), Civil Government (Civil Gov't), and Commercial. The chart was created on Nov. 8, 2017 using data from M. Swartwout[11].



(a)



(b)

Figure 2. (a) 3D-printable satellite model and embedded electronics used in ENEE 4999: Embedded Systems for Space Applications, and (b) NASA's 1U PhoneSat 2.5[12] for comparison.

Figure 2(a) illustrates a 3D model of a custom CubeSat development kit used by students in the ESSA course and Figure 2(b) shows the 1U PhoneSat 2.5 developed at NASA's Ames Research Center for comparison[12]. The development kit includes a low-cost, 3D-printed model of a 1U CubeSat chassis, commercial off-the-shelf (COTS) flight computer options using ATMega328 (Arduino), Texas Instruments MSP430, or Parallax Propeller microcontroller units (MCU), and a sensor interface nominally including GPS, temperature, and pressure sensors. The kit and core software allows for interfacing with a web server via a RaspberryPI, which allows for remote access and control of the device in a laboratory setting. In-flight communication is achieved via the ham radio Automatic Packet Reporting System (APRS).

High-Altitude Balloon Launch Demonstration

Unmanned high-altitude balloons (HAB) are used as low-risk launch vehicles for testing and demonstrating the student payloads. Figure 3 illustrates a notional image of the HAB platform including the latex balloon, parachute, radar reflector, and payload carrier for housing electronics, science experiments, or completed CubeSat development kits. The HAB system uses Helium for lift and is designed to reach altitudes between 30-35 km. Burstable balloon envelopes are generally used to start descent, though an altitude- or radio-controlled cut down mechanism may be employed.

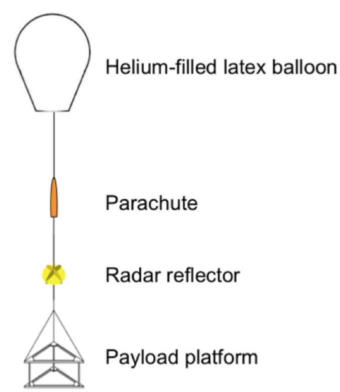


Figure 3. Basic HAB rig used for launch of student projects.

ENEE 4999: Embedded Systems for Space Applications

Overview: The ESSA course primarily involves team projects with the goal to launch a sub-orbital balloon carrying a CubeSat spacecraft by the end of the semester. The CubeSat is intended as a vehicle for conducting sub-orbital high-altitude science experiments or as a test vehicle for orbital experiments in association with research activities at UTC focused on the impacts of the space environment on the reliability of electronics systems. Teams of 2-3 undergraduate students are formed on the first day of class. Each team focuses on the design, development, testing, and reporting for a HAB or CubeSat subsystem. The subsystems include:

HAB structure including the balloon, parachute, payload, and sub-payload assembly, flight computer, power system, telemetry and tracking systems, communication, video, and experimental sub-payload modules. The spring 2016 and 2017 semesters included 11 and 9 students, respectively, divided into 4-5 teams each.

Schedule: The 14-week course is arranged to have two meetings per week on Tuesday and Thursday. Two weeks following the course are reserved as for the HAB launch window. In the case of spring 2017, the launch was conducted during the following summer semester in order to align with the Aug. 21, 2017 solar eclipse. In a typical week, Tuesday is used for group meeting or journal club, and Thursday is reserved as a laboratory workday. The schedule is as follows:

Weeks 1-3: Split into teams, perform early self-assessments, and develop project proposals.
Week 4: Submit updated project proposals and detailed budget requests.
Week 8: Preliminary design review.
Week 12: Critical design review.
Week 14: Finalize projects and submit Users' Guides, and Developers' Guides.
Weeks 15-16: HAB launch.

Group Meeting: During group meeting, the instructor asks for either informal or formal project updates. Informal updates include a general discussion on status, project organization, team interfacing, or a question/answer session to address technical hurdles. These discussions occur in a round-table format (*i.e.*, the instructor is seen as a collaborator) where students are encouraged to discuss challenges and problems faced. The focus of these discussions is more on the challenges and failures, rather than successes. Possible solutions to the students' challenges are debated and students leave with plans moving forward. Formal project updates include delivery/discussion of the project proposal (document), proposed budgets (document), preliminary design review or PDR (presentation), critical design review or CDR (presentation), and final documentation in the form of a payload User's Guide as well as a Developer's Guide. The focus of the formal updates is on the project successes.

Journal Club: In addition to group meeting, each student is required to participate in journal club. Each student must host one journal club meeting. The host recommends a conference proceeding or journal article at least 1 week prior to the journal club, offers an overview and critique in the form of a presentation, and moderates a debate/discussion. Topics for the journal club must be in the areas of embedded systems, real time operating systems, space sciences, space electronics, or an area approved by the instructor. The instructor and students evaluate each journal club presentation. Additionally, the instructor scores participation in the discussion. Journal club serves three primary purposes. First, students learn to conduct proper background literature searches through databases such as the IEEE *Xplore* Digital Library[13]. Second, students learn to evaluate the quality of the scholarly work through examination of the writing, reproducibility, peer review, impact factors, reputation of the journal, and number of citations and text views. Finally, students learn how to apply their findings to the benefit of their projects.

Laboratory Workday: At least one day per week is dedicated to laboratory work focused on the design, simulation, and construction of the student payloads. Discussion and collaboration is a critical portion of these sessions. Students work closely with their colleagues on solving problems and developing solutions. The instructor is present to provide technical guidance.

Reflection: While experience is the basis for learning, it cannot be assumed that learning occurs with experience[14]. Reflection is therefore used to engage the learners to re-capture, notice, and re-evaluate their experience[15]. Throughout the design cycle, and achievement of project milestones, students are asked to complete a pre-experience reflection and survey, log weekly status updates in a journal, complete critical reflection and self-assessment throughout the experience, and complete a post-experience reflection and survey.

Pre-experience reflection activities include the identification of a problem/challenge, self-assessment of skills required to solve problem/challenge, reflection of current skillsets, and the proposal of a possible path/direction for acquiring new skills appropriate for solving problem. Weekly status updates are short bullet lists of activities related to the design project, highlights of any important findings, mention of any challenges and proposed solutions, and documentation relevant to other teams. Critical reflection activities include the assessment of outcomes following proposed solutions, analysis of alternative solutions, and reflection of progress towards development of new skills. This activity occurs on a weekly basis and is included in the laboratory journals. Post-experience reflection activities include the self-assessment of designs, reflection on new skills, reflection on skillsets before and after classroom experience, and analysis of the direction chosen for development of skills appropriate for solving problem. In addition, students are asked to complete a survey documenting their perceptions of their skills before and after taking the course, and for solicitation of feedback.

Intangible Elements: Various intangible aspects of the course are critical to facilitating a successful dynamic classroom. First, *mutual respect* is a cornerstone principle, meaning that not only do students and teacher treat each other with respect, but also students must treat each other appropriately. When students realize that they are in a dynamic environment where the solutions may not be known or understood, they tend to respond favorably when the instructor looks to them for the answer (*i.e.*, the instructor allows the student to teach others). Further, the process is not about demonstration of specific technical knowledge, but more about learning methods for gaining the knowledge required to solve a problem. As such, a second intangible item is the *tolerance for failure*. Rather than punishing the students for lack of knowledge at a particular point during the process, students are awarded for their ability to recognize when a failure occurs and their ability to navigate to a solution in the midst of failure. This is achievable through a project organization that offers high reward (*e.g.*, the successful launch of a payload to near-space), with high risk (*e.g.*, the probability of a failed component is substantial especially given the short design cycle) at low consequence (*e.g.*, under the protection of their academic pursuits rather than in professional settings). As described in the following student comment (spring 2017), students recognize the opportunity for growth through failure.

> "I have failed at projects or assignments in this course and in other courses, and instead of punishing me for failing, he promotes learning from your mistakes and rewards correcting those mistakes."

Assessment

ESSA was designed to reinforce five primary student outcomes related to the criteria for accrediting engineering programs derived from the ABET Engineering Accreditation Commission (EAC)[16]. Students are able to: (1) design a system, component, or process to meet desired needs, (2) identify, formulate, and solve engineering problems, (3) use the techniques, skills, and modern engineering tools necessary for engineering practice, (4) demonstrate an ability to communicate effectively, and (5) recognize the need for, and an ability to engage in life-long learning. Two types of assessment methods were used to evaluate these outcomes, in addition to various other skills: instructor assessment of select outcomes, and self-assessment through a pre-course and post-course survey. Skills were assessed on a scale of 1 (low ability or poor) to 5 (high ability or excellent). The following sections detail assessment results from the spring 2017 semester. Formal assessment the spring 2016 student outcomes was not conducted.

Table 1. Student outcomes assessed, along with associated performance indicators and student artifacts.

Student Outcome	**Performance Indicator**	**Student Artifact**
(1) Design a system, component, or process to meet desired needs	Student clearly provides problem statement, derives objectives, notes associated boundaries or constraints, provides alternative designs, and completes final design to meet objectives.	Developer's Guide
(4) Demonstrate an ability to communicate effectively	Student provides critique of technical journal through presentation of subject matter, moderates a debate/discussion amongst peers, and presents key ideas and findings clearly.	Journal Club Presentation

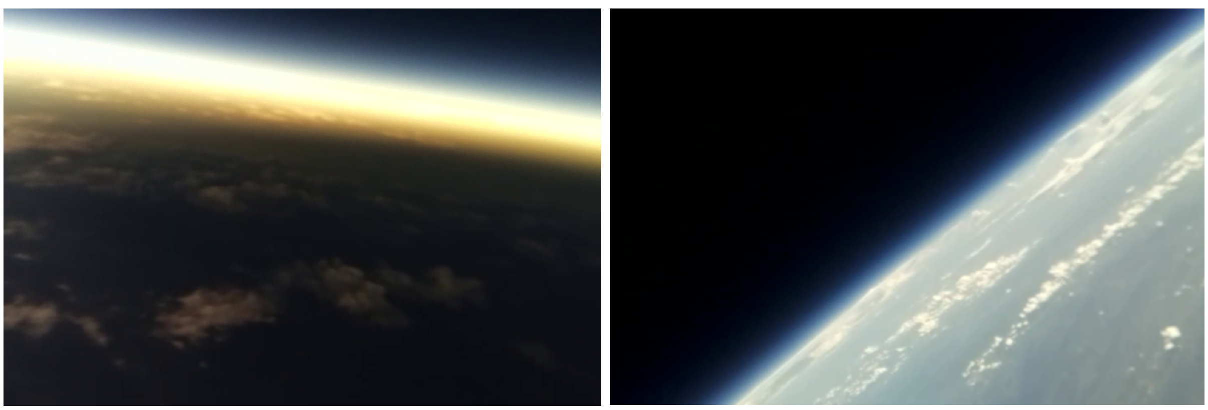
Table 2. Survey results of student self-assessment of skills before and after course in the spring 2017. Skills were assessed on a scale of 1 (low ability) to 5 (high ability). Mean (μ) and standard deviation (σ) are provided. Response rate was 88.9% (8 out of 9 students). The paired sample t-test was used to examine significance of the difference in observed means.

	μ (σ)	
Skill	**Pre**	**Post**
Ability to use scientific principles to analyze a problem/process*	3.5 (0.8)	4.0 (0.8)
Ability to use engineering principles to analyze a problem/process**	3.8 (0.5)	4.4 (0.5)
Ablity to design an experiment*	3.1 (0.6)	4.0 (0.0)
Ability to design solutions to meet desired needs**	3.3 (0.7)	4.1 (0.4)
Ability to convey technical ideas verbally**	2.6 (1.1)	4.0 (0.5)
Ability to convey technical ideas in writing*	3.0 (1.1)	4.0 (0.0)
Ability to present in front of your colleagues/peers*	2.9 (1.0)	4.1 (0.6)
Ability to apply engineering skills (programming, circuit design, etc...)**	3.6 (0.7)	4.4 (0.5)
Ability to read and critique technical literature**	2.0 (0.5)	4.0 (0.0)
Ability to locate quality technical literature**	1.8 (0.7)	3.8 (0.5)

**(p-value < 0.05)*
***(p-value < 0.01)*

Student Performance: Formative assessments of student outcomes (1) and (4) were conducted to gauge the students' abilities to design a system or sub-system to meet the strict constraints of a spacecraft, and to communicate the designs and findings through documentation and presentation. The performance indicators and associated student artifacts used for assessment are provided in Table 1. The average scores were 3.7/5.0 and 4.0/5.0, for student outcomes (1) and (4), respectively. The standard error in measurement was approximately 1.3 in each case. Additionally, 63% and 88% of the students received marks of 4 or higher for student outcomes (1) and (4), respectively.

Student Self-Assessment: Table 2 shows results of student self-assessment of skills (before and after course) in the spring 2017. Mean (μ) and standard deviation (σ) are provided. The response rate was 88.9% (8 out of 9 students). The paired sample t-test was used to examine significance of the difference in observed means. A single asterisk is used to represent p-values less than 0.05, and a double asterisk is used to denote p-values less than 0.01. On average students perceived improvement in each category, with the largest increases in the ability to discover, read, and critique technical literature, use engineering principles to analysis of a problem, apply engineering skills to practical problems, and design a solution to meet a desired need.



(a) (b)

Figure 4. Example images captured by student-designed HAB and payload system (MOC-2). Images were captured on Aug. 21, 2017 and show (a) the Earth at approximately 10.5 km in the shadow of the Moon during eclipse totality, and (b) Tennessee from approximately 30.5 km. MOC-2 reached a peak altitude of approximately 33.8 km.

Discussion

The spring 2016 offering resulted in a successful design, launch, and retrieval of the first version of the HAB system named MOC-1. The mission of MOC-1 was to demonstrate a HAB launch vehicle and tracking capability. The second version, MOC-2, was launched following the spring 2017 semester during the Aug. 21, 2017 solar eclipse. The primary goals of MOC-2 were to demonstrate a robust power regulation system capable of sub -50°C operation, and to capture aerial photography of the Earth's surface within the path of eclipse totality in the southeastern region of Tennessee. Figure 4 illustrates some sample images captured during the flight. Payload assemblies included a custom power system for operation down to approximately -70 °C and a RaspberryPI-based camera system to capture video of the entire flight, in addition to the standard sensor kit previously described. In both cases, approximately 50% of the student payloads were included on the flights. Payload assemblies were not included if they were deemed to pose a significant risk to the mission success, or presented a safety concern. However, surveys indicate that the majority of students were engaged with the hands-on activities and appreciated the opportunity contribute to a successful project with tangible outcomes.

Assessment results from the spring 2017 semester indicate excellent student performance with respect to the students' abilities to communicate findings through documentation and presentation. It is likely that the journal club presentations and discussions, and the continuous demand on the students to reflect, discuss failure, and coordinate with colleagues contributed to the students' increased competence in this area. Journal club was generally the students' least favorite portion of the course, as documented through self-assessment, but appears to result in the largest gains in student knowledge and experience. Also, the quality of the journal club presentations/debates generally improved throughout the semester as students learned from each other how to locate higher quality articles, evaluate technical merit, and understand journal impact factors.

Assessment of the students' ability to design a system or sub-system to meet the strict constraints of a spacecraft were favorable. While approximately 50% of the payloads generated during the spring 2016 and 2017 offerings have been approved for launch, the majority of students end the course with a functional prototype. In the future, more time will be devoted to understanding mechanical and assembly issues in order to improve the number of payloads approved for flight. There seems to be a significant disconnect between rapid prototyping at the breadboard level and completed and mechanically sound assembly. Further, it is not clear given these data if students' successes are representative of their abilities to design and prototype prior to entering the course, a result of improved abilities throughout the course (students certainly perceive improvements in skill), or a result of reinforcement of current knowledge. Attempts to objectively assess student outcomes (1), (2), and (3) prior to participation as well as following the conclusion of ESSA will be conducted in future course offerings. Finally, the hands-on experiential learning approach appears to be a useful approach for enriching student outcomes in culminating courses such as ESSA, where more focus can be spent on problem solving, teamwork, communication, and application rather than on skills and knowledge development.

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