Developing an Integrated Curriculum for Small Satellite Engineering

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An ongoing challenge in undergraduate engineering education is creating a meaningful design curriculum that integrates disciplines and provides hands-on experience for students to learn about science, engineering, and organization management. The U.S. Air Force Academy (USAFA) has attempted to address this challenge by developing a multi-disciplinary program for undergraduate students to "learn space by doing space." This program challenges students to design, build, test, launch, and operate a small satellite as part of their course of study. We have found that this program significantly enhances the ability of our students to create aerospace systems in the presence of ambiguity and complexity.

The USAFA small satellite program achieved a significant milestone in October 1997 with the successful launch and operation of the Falcon Gold spacecraft—a student-built experiment to detect GPS signals from near-geosynchronous altitude. Since that time we have been developing FalconSat-1—our first free-flying satellite—for launch in late 1999. Over the course of developing Falcon Gold and FalconSat-1, the small satellite curriculum has matured into a four-semester sequence of courses in spacecraft engineering. Throughout the sequence, students and faculty from multiple disciplines and academic departments play key roles in the development process. In addition, we receive support from several other capstone design projects to address specific needs of the small satellite program.

As with any major curriculum effort, operating a small satellite program with undergraduate students can be a formidable task. In particular, our program requires a substantial commitment of faculty expertise, laboratory resources, external consultants, and funding. These strategic assets must be managed carefully to achieve program objectives. Nonetheless, overcoming these challenges allows for substantial student learning to occur, which is the fundamental reason for this program. Our experience is that both group learning and independent thinking are enhanced, and the curriculum provides first-hand experience in the development of space technology as well as opportunities for discovering new knowledge.

I. Program Objectives and Background

Our fundamental goal with the USAFA small satellite program is to provide a broad, applications-oriented experience of space technology for our undergraduate students. Technology can be defined as the "application of science, engineering, and industrial organization to create a human-built world."[1] Designing, building, and operating a small spacecraft is the focus for experiencing all these aspects of technology. The specific objectives of the USAFA small satellite program are to:

(1) motivate cadets toward space by providing “real world” satellite design, fabrication, test, launch, and operational experience;
(2) enhance the Air Force Academy curriculum by providing the framework for a series of capstone courses in engineering and space systems design; and
(3) support Department of Defense research and development initiatives by flying space experiments with valuable military applications.[2]

As cadets tackle these challenges they learn many of the hands-on engineering disciplines required for building a spacecraft. The cadets at the Air Force Academy have several constraints on their availability and expertise that have practical implications for our program. The USAFA curriculum is demanding and rigorous both academically and physically. Cadets have a very full academic schedule that is augmented with military, athletic and airmanship training.

Despite the constraints on USAFA cadets, we aim to enhance the undergraduate engineering curriculum by providing a series of capstone courses in engineering and space systems design centered on small satellite issues. The centerpiece of this curriculum is a four-semester sequence in satellite design and engineering offered in the Department of Astronautics. The first two courses in the sequence are offered to second-class cadets (juniors), primarily in a traditional lecture/discussion format to provide students with the fundamental theory and techniques of spacecraft subsystem analysis and design (Astronautics 331 and 332, see Table 1). The first-class cadets (seniors) then enroll in the small spacecraft engineering sequence (Engineering 433 and 434). These courses are laboratory design courses where the students are responsible for systems engineering, management, fabrication and operation of their satellite program.

Table 1. Small Satellite Related Courses for Academic Year 1998-99.

Course No.	Course Name	Contribution
Astro 331/332	Space Vehicle Design I & II	Small Satellite Pipeline for next year
Engr 433/434	Small Spacecraft Engineering I & II	Build FalconSat (Cadets from eight academic majors)
Engr 410	Engineering Systems Design	Build Spacecraft Handling Fixture & Stand
Comp Sci 453/454	Software Engineering I & II	Develop Ground Station Software
Astro 491	Senior Research and Thesis	Design Attitude Control Testing Apparatus
Comp Sci 499	Independent Study	Develop Software Test Procedures and Ground Station Simulator
Physics 499	Independent Study	CHAWS Experiment Hardware Calibration, Integration, and Test

The full four-semester sequence of spacecraft design and engineering classes is a key component of the curriculum for cadets majoring in astronautical engineering. One method to increase involvement across other academic disciplines has been to allow interested students to enroll in the senior-level laboratory classes (Engr 433/434) without taking the junior-level classes in satellite subsystems (Astro 331/332). This enables us to form a team with the appropriate mix of skills needed to design and build a satellite. We have involved cadets from seven academic majors (computer science, electrical engineering, engineering mechanics, engineering science, management, space operations, and physics) in addition to astronautical engineering during the 1998-99 academic year. These students bring a more detailed academic background to specific aspects of satellite design (software engineering, for example), but they lack some of the fundamentals of space mission analysis and design needed to fully participate in the design process. We address this potential shortcoming in two ways. First, we offer an "Astro Primer"—a short series of introductory lectures, homework problems, and exams—to provide some of the fundamentals of orbital mechanics and satellite design. Second, we assign all students to a team to work together on a subsystem, typically with astronautics majors filling roles as project manager and systems engineers. For example, we team cadets from the electrical engineering department with strengths in circuit design with cadets from the astronuatical engineering major who are strong in attitude determination and control. This combination has two advantages: students with strong academic backgrounds in relevant disciplines improve the overall quality of our designs, and students from a broader spectrum of departments are able to participate in the program.

Faculty participation in the small satellite program spans six academic departments (astronautics, computer science, electrical engineering, engineering mechanics, management, and physics). The faculty members serve as mentors for the cadet design teams. Mentorship of a cadet team requires a close working relationship with the students to guide their progress, provide experienced advice to their design and fabrication efforts, and regulate their frustrations when dealing with the complex and ambiguous task of developing a spacecraft. Technician support is somewhat more problematic for a new program. Laboratory technicians are shared with other courses and requirements, and are not always available to support the needs of the program.

The additional courses listed in Table 1 supporting small satellite objectives spread spacecraft technology throughout other parts of the USAFA curriculum. In particular, the senior-level engineering design course (Engineering 410) is a core requirement for all cadets at the USAF Academy regardless of academic major. The course is a capstone engineering design and development class requires delivery of a working final product. Several projects supporting small satellite program needs have been completed through Engr 410. For example, one class built a dust-free clean tent for spacecraft fabrication; another built a mechanical assembly stand to orient and manipulate the satellite while it is being built. These Engr 410 projects are much less complex than the overall satellite—the students only have one semester to complete their projects instead of several, and the projects need to be built by cadets from non-technical disciplines. The projects provide useful infrastructure for the small satellite program while enabling the Engr 410 to contribute to the small satellite program and to see their project become an important and well used piece of equipment for the small satellite laboratory.

One of the driving considerations for our program is the desire to have every graduating class launch and operate an aerospace vehicle. Unfortunately, annual space launches are not practical for a number of reasons, principally cost and development time for a new mission. In the interim years between space launches we launch and operate high-altitude research balloon payloads with prototype designs. This provides students with the opportunity to command their "balloon-sat" and receive telemetry for a mission to altitudes in excess of 100,000 ft. The overlapping sequence of development activities and the hand-off from one class to the next allows for a small satellite development spanning several years (see Fig. 1).

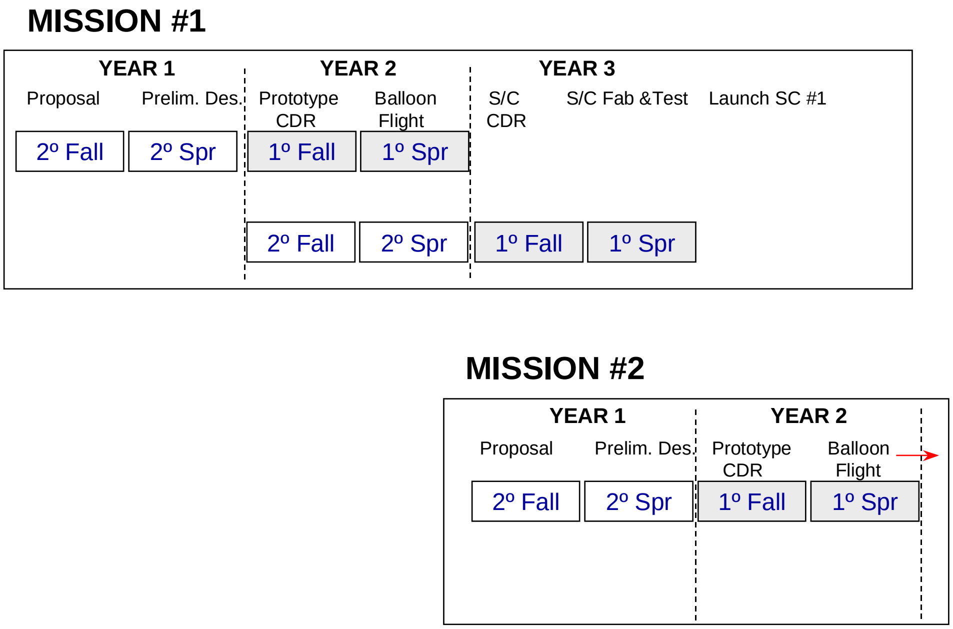

Figure 1. Course Sequence for Small Satellite Development. Diagram shows overlapping development from one graduating class to the next to enable a multi-year development cycle, based on a nominal three-year development with a space launch every two years. The notation 2º indicates second class cadets (juniors) and 1º indicates first class cadets (seniors).

In the past four years small satellite classes have successfully launched four high-altitude research "balloon-sats" and one space vehicle. Our next launch, FalconSat-1, is planned for late 1999, and FalconSat-2 is projected for 2002 (see Table 2). The next subsection describes the current satellite our students are building, FalconSat-1.

Table 2. Small Satellite Program History. Summary of balloon flights and space launches under the USAFA Small Satellite Program.

Date	Event	Satellite	Mission
May 1995	Balloon flight	USAFASAT-B	Attitude Control Demonstrator
Mar 1996	Balloon flight	Glacier	GPS & Magnetometer Experiment
Sep 1996	Balloon flight	PHOENIX	Laser Communications Demo
Apr 1997	Balloon flight	FalconGold	GPS Signal Capture
Oct 1997	Space launch	FalconGold	GPS Signal Capture
Sep 1999	Space launch	FalconSat-1	CHAWS-LD (Spacecraft charging experiment)
Aug 2002	Space launch	FalconSat-2	Propulsion Technology Demonstration

FalconSat-1 Mission Overview. FalconSat-1 is a small satellite carrying the Charging Hazards and Wake Studies-Long Duration (CHAWS-LD) experiment. The purpose of the mission is to determine the effects of spacecraft charging in a low-earth orbit over a time period of at least six months. The primary objectives of the mission are to: (1) Provide data that will allow scientists to analyze the effects of charging on spacecraft in low-earth orbit over an extended time period; (2) Validate FalconSat-1 system design by transmitting telemetry data, gathered by the different subsystems of the spacecraft bus, to the mission control center; (3) Provide a flight experience with new computer hardware and software developed for the program; (4) Provide a ground station test bed for education and training purposes and allow cadets to gain hands on experience in space operations.

The payload concept to perform the physics measurements is straightforward. On each side of the spacecraft, voltage and current sensors are installed. When FalconSat-1 moves through the space plasma environment it creates a wake behind it where electrons are accumulated. The bow side of the spacecraft will have a build-up of positively charged ions, resulting in a net electtic potential across the spacecraft. The current and voltage sensors on the four sides of the spacecraft will measure these charging effects over the lifetime of the satellite and in different regions of the earth's geomagnetic field.

FalconSat-1 will be launched on the first flight of the Minotaur launch vehicle, a program to convert excess Minuteman II ballistic missiles for orbit insertion. Mission duration is planned to be about two years. The Mintaur launch vehicle will deliver FalconSat-1 into a circular, nearly sun-synchronous orbit at an altitude of 750km and inclination of 100 deg.

The FalconSat-1 spacecraft is roughly a cube, 17 in tall and 18 in on each side, and consists of six main subsystems: Electrical Power Subsystem (EPS); Communications; Command, Telemetry and Data Handling (CT&DH); Attitude Determination and Control (ADACS); Payload (CHAWS-LD), and Structure (see Fig. 2). The first four subsystems are mounted in aluminum trays that make up the frame stack assembly. The four transmit antennas are mounted at the bottom of the spacecraft and the receive antenna is on the top. The solar panels and CHAWS-LD sensors are mounted on the outside of the spacecraft.

Future Initiatives. The unique environment for interdisciplinary learning that has been established through the small satellite program continues to grow, and we are beginning to formulate our next mission, FalconSat-2. FalconSat-2's mission is to test critical technologies for formation flying and maneuvering of future military satellites. Specifically, the spacecraft will provide a flight demonstration of hybrid propulsion systems using solid propellants and liquid oxidizers to maneuver a small satellite. USAFA cadets will primarily perform the design, fabrication and test of FalconSat-2 as part of the USAFA small satellite program. Developing new satellite maneuvering techniques is critical for future DoD space systems that will require active formation flying, threat avoidance, station keeping, and proximity operations. These capabilities will enable future generations of military nano-satellites to support U.S. information superiority and support aerospace dominance. The Air Force Research Laboratory has outlined DoD research needs for space missions using large clusters of micro-satellites. One of these concepts, dubbed TechSat 21, involves satellites flying in formation and operating cooperatively to perform a variety of missions.[3]

II. Challenges

As one might expect, a project with the complexity and scope of a small satellite development brings with it a host of technical and programmatic challenges. The challenges faced at the Air Force Academy fall into three general categories: resources, core competencies, and difficulties associated with implementation at an undergraduate level.

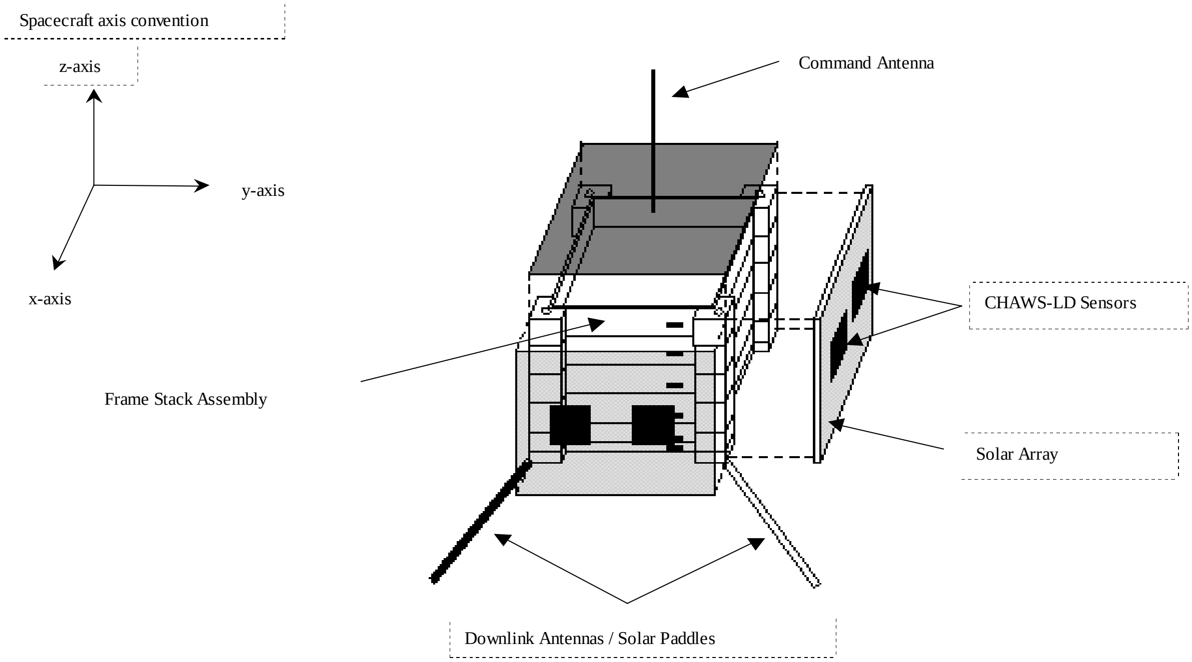

Figure 2. FalconSat-1 Configuration. Drawing shows key features of the spacecraft design. Each tray in the frame stack assembly houses a separate satellite subsystem. The CHAWS-LD sensors, the solar arrays and the communications antennas are mounted on the exterior surface.

Resources. Spacecraft development is a resource intensive effort that requires adequate funding, infrastructure, and personnel. The bottom line is that satellites are not cheap to build, launch, and operate. FalconSat-1 costs for fabrication and test total about $500K. Roughly half the cost was for space-qualified hardware including communications equipment, computers, batteries, and solar arrays (the arrays themselves cost $140K). Although $500K is cheap by commercial satellite standards, it exceeds the annual “institutional” funding the small satellite program receives as one of the Academy’s six research centers (approximately $150K). Additional funding for the program had to be secured from other sources. Much of the remaining funds required for FalconSat-1 were provided through the DoD’s Space Test Program (STP) which sponsored the CHAWS-LD experiment.

The Academy was fortunate to receive a free launch for FalconSat-1 aboard the new DoD-sponsored Minotaur launch vehicle. Launch services for small spacecraft typically exceed $1M, depending on the size of the satellite and its desired orbit. Like many institutions, we cannot afford to pay the going rate for launches and have to seek other options. Because the USAFA is a DoD organization we have access to unique opportunities. For example, FalconGold was launched on a Lockheed-Martin Atlas II rocket carrying a DoD communications satellite as its primary payload).

Once the on-site ground station is functional, costs for operations to track and control orbiting USAFA spacecraft will be relatively small. FalconSat will pass within contact range of the Academy 4 to 6 times a day. Cadets operating the ground station will handle most of the short-duration passes (10-15 minutes).

In addition to funding, a key resource for spacecraft development is the availability of specialized facilities and equipment. A university-level program to build a small satellite requires dedicated laboratory resources, including technical support and facilities. We our fortunate at the Air Force Academy to have access to many excellent facilities to support our program. The Astronautics Laboratory occupies approximately 17,500 square feet of space dedicated to lab activities, equipment, classrooms, and offices. Only about 1,000 square feet of space is dedicated to satellite fabrication and ground station equipment, but key infrastructure in the lab is available for our use, including:

- Satellite Fabrication lab including 100,000 class clean tent and laminar flow bench
- Electronics laboratory for breadboarding and testing circuits
- Engineering laboratory for mechanical fabrication
- In-house machining capability
- Thermal cycle chamber
- Printed circuit board design and fabrication capability
- Test equipment (oscilloscopes, spectrum analyzers, power sources, frequency generators, computers, antennas, etc.)
- USAFA ground station and PicoSat ground control equipment (provided by the Air Force Space and Missile Center)
- Conference room and common-use computers

In addition, laboratory facilities and technicians from other science and engineering departments at USAFA are available to support the Small Satellite Program if needed. Frequently used capabilities include:

- Numerically controlled milling machines (Training Devices Department)
- Vacuum chamber (Department of Physics)
- Structural vibration test equipment (Department of Engineering Mechanics)

Although the Academy has developed much of the necessary infrastructure to support such projects, we have to seek external support for some tasks, particularly system-level environment testing. For FalconSat, we are planning to perform vibration and thermal-vacuum testing of the spacecraft at Air Force Research Lab (AFRL) facilities at Kirtland AFB, NM.

External partnerships, like the one with AFRL, are vital to the success of our program. In addition to providing necessary services, these collaborative arrangements can also provide critical hardware. The Academy entered a Cooperative Research & Development Agreement (CRDA) with United Technologies Microelectronics Corporation (UTMC) to produce two embedded controllers for the flight computer system. In return for the hardware the Academy will give UTMC the opportunity to space qualify their new product by flying the controllers on

FalconSat-1 producing a win-win situation. These external partnerships also help educate our students about the capabilities of the greater aerospace industry.

Core Competencies. Building a satellite requires people with a variety of specialized technical skills. Though we try to assemble to right “skill mix” on the cadet and faculty team there are some key competencies that are not available in-house. To compensate for these shortcomings we routinely contract out for the necessary support. This accomplishes the mission but adds a financial burden to the program. An important consideration when using contracted help is the interaction with the cadets. The contractors understand that an essential part of their job is to educate our students as they help build and test the satellite, which has worked very successfully in the past.

A significant problem is the lack of true spacecraft engineering experience on the faculty. Most of the faculty are Air Force officers who come from a variety of professional backgrounds. Some have operated aerospace systems or have managed acquisition and development of such systems in previous assignments. As such, military faculty members have a more general engineering background. They can proficiently serve as mentors for much of the spacecraft development work but do not have the hands-on fabrication experience that comes from working in a production facility. The issue is compounded because military faculty remain on staff for less than four years on average, taking with them the knowledge gained during their Academy tour of duty. To mitigate the problem, the Academy has instituted an endowed chair position filled by an individual with the requisite spacecraft experience. The current Shriever chairholder, Prof Emery Reeves, worked for TRW for over 30 years designing and building satellites and rockets. His contributions to our FalconSat program have been invaluable.

Another core competency not typically available among Air Force officers is experience with balloon operations. The Academy contracts for ballooning expertise when we fly a prototype spacecraft on a high-altitude research balloon. Though the Academy has the necessary hardware to outfit a mission, it is again a matter of experience. Flying a balloon every couple of years is not sufficient to gain the necessary experience and confidence to execute such a precision operation.

In addition, the Academy lacks enough technicians with the specialized skills to perform space-quality fabrication work, especially soldering of wires to connectors, harnesses, and printed circuit boards. As a result we hired three technicians during the critical assembly period of FalconSat-1 to do this type of work. Cadets were able to help with the effort by building related hardware like electrical breakout boxes and assembly jigs, and they tested the competed wiring harnesses to verify that the product was built properly to the drawings.

In the software realm the Academy has sufficient capability to develop structured programming code (Ada, FORTRAN, C++). Our curriculum does not, however, stress the development and use of real-time operating systems (RTOS) needed for multi-tasking the various spacecraft functions. We purchased a commercial RTOS and its associated training for use on FalconSat-1. Our software engineering cadets focus on writing and debugging application code which interacts with the operating system software.

Undergraduate Curriculum. A major challenge we face in our small satellite program is the lack of graduate researchers. Unlike research institutions that have graduate students available to work such projects essentially full time, we must rely on undergraduates to execute the program. Although the Academy attracts some of the best students in the country, the reality is that time is a valuable commodity here. Cadets in engineering majors often take more than 20 credit hours of course work a semester. In addition, cadets have military duties to perform as well as required physical training. Many cadets are also involved in various aviation programs like flight training and parachuting. From the cadet perspective, the small satellite engineering course is just one of six or seven they may have in a given semester. Fortunately, many cadets are motivated by the project to put in the necessary time to get the job done.

III. Learning Outcomes and Teaching Strategies

Creating a series of courses focused on the design, development, and operation of a spacecraft requires careful planning to achieve the desired learning outcomes. The objective of any interdisciplinary course is to "develop an integrated approach to inventing the subject."[4] Our subject, of course, is a small satellite, and the inventive and creative process needed to produce a satellite design requires the disciplines to come together in a new way.

The specific learning objectives we hope to achieve in the small satellite program span the range of cognitive development. Although we teach a senior-level, project-focused course, we need to provide a common foundation of knowledge to bring students from a variety of disciplines (academic majors) on board. Ultimately, our objective is to have the students gain an ability to think critically and synthesize information more completely by the end of the academic year. Table 3 summarizes our learning objectives for the small satellite curriculum, and links these outcomes to the cognitive hierarchy contained in Bloom's Taxonomy of Educational Objectives.

Table 3. Small Satellite Program Learning Objectives. Table shows desired learning outcomes paired with the associated level of Bloom's Taxonomy.

Small Satellite Learning Outcome	Bloom's Taxonomy
Fundamentals	Knowledge
Independent Thinking	Comprehension
Applied Technology	Application
Group Work and Interdisciplinary Involvement	Analysis
Dealing with Ambiguity and Complexity	Synthesis
First-hand Experience with the Project Life Cycle (design through operations)	Evaluation

Fundamentals. For the first dozen or so class meetings in the Fall semester we split the class into two groups for instruction—Astronautical engineering majors in one group and all other students (electrical engineers, computer scientists, etc.) in the other group. The "Astro group" studies fundamental topics in spacecraft electronics and fabrication techniques. The "non-Astro group" studies material in Astronautics such as orbital mechanics and space mission analysis. This background provides a basis for applying more advanced skills throughout the subsequent design and fabrication process.

Independent Thinking. In addition to demonstrating their comprehension of the fundamentals through an exam, students must exhibit independent thinking by completing their numerous assigned tasks. These task assignments flow from the students' internal organization and management structure (see Fig. 3).

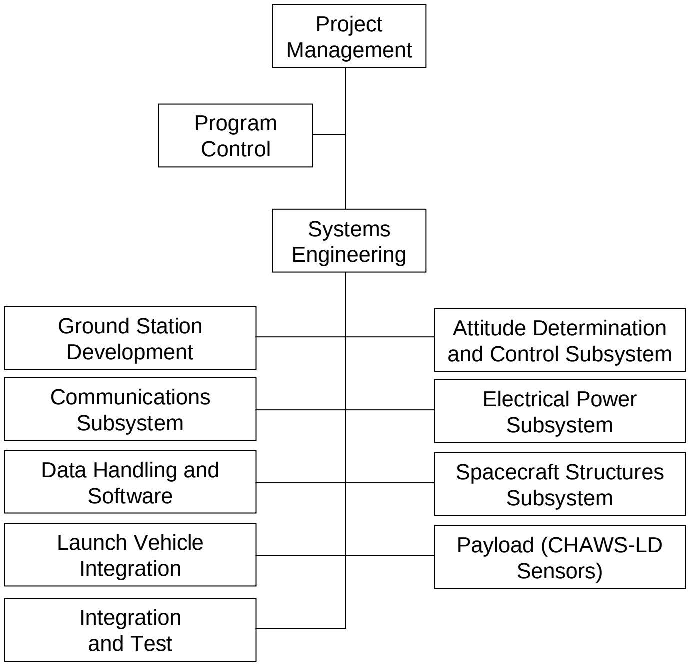

Fig. 3. Small Satellite Student Team Organization. Each team contains students and at least one faculty mentor. The program control function includes scheduling, budgeting, contracting, and configuration management.

Applied Technology. The small satellite design process provides many opportunities for cadets to apply technical knowledge from their chosen field of study. For example, an attitude control system employing a magnetic torque rod requires careful design with respect to spacecraft dynamics, electronic control circuitry, electromagnetic behavior, and thermal and structural properties. Subjects the students have mastered in other courses must be applied to new situations, infusing technical knowledge of specific technical subjects into a satellite application.

Group Work and Interdisciplinary Involvement. The formation of functional groups and the explicit inclusion of students from multiple academic majors is an important part of our pedagogical construct. Our goal with these groups is to raise the level of communication about a topic to enhance a deeper analytical understanding of the systems nature of a satellite design. Every aspect of the design, such as a circuit board for conditioning telemetry data, must be considered from a variety of perspectives: electronic circuit design, mass properties, thermal environment, power consumption, physical dimensions, mounting techniques, and assembly and test procedures. Figure 4 shows a cadet team working with space flight components in our laboratory. Analyzing and communicating these various design elements becomes a key challenge for every component of the spacecraft, and every student team working with these components.

Fig. 4. Spacecraft Fabrication Activity. Cadets First Class Jim Taggart, Justin Hendricks, and Scott Karl (left to right) prepare to test the communications system modem in the small satellite clean room located in the Astronautics Laboratory at the USAF Academy.

Dealing with Ambiguity and Complexity. When faced with the task of producing a workable engineering design there is no single correct answer—and an infinite number of wrong answers (approaches that simply won't work). The ambiguities encountered when implementing the systems design process, and the complexity and interconnectedness of an operational space vehicle, require a high degree of synthesis to perceive alternative methods and develop approaches for evaluating these untried methods.

First-hand Experience with the Project Life Cycle. Over the course of the academic year, our students create a design and bring it to reality, either as a balloon prototype or as a space vehicle. This first-hand experience of the process, the successes, failures, and compromises required to make something work, provides a framework for them to judge future projects they participate in after graduation. This experience allows them to assess the worth and viability of alternative courses of action. This evaluative basis—derived from their own personal experiences—provides standards that our graduates can use to appraise choices in their everyday professional environment. Figure 5 shows the development of our mission ground station which will be used during the operational phase of our project.

Fig. 5. USAFA Ground Station. Cadet First Class Jeff Liegl prepares the FalconSat ground station for mission operations.

Teaching Strategies. We employ several teaching strategies to facilitate our desired learning outcomes. The key element of our strategy is to involve a large number of faculty in the education process. We maintain communication and continuity of purpose through frequent team meetings (2-5 per week), typically attended by more than a dozen faculty members, project consultants, and students. Only three instructors are assigned to the small satellite courses, but faculty volunteers participating in the project work closely with small teams of 2-3 students to guide the progress of the project. We refer to these faculty volunteers as “mentors” because it is their responsibility to guide the learning process and ensure the project gets completed. The mentors provide discipline-specific guidance to the students on each of the subsystem teams and ensure their team is staying on schedule to complete their designs.

The elements of the teaching process employed by mentors require a balance of ideas about learning. The mentoring process requires the mentors to understand the needs of their student team and the constraints of the overall program. The specific tools mentors use to foster learning on their teams include[4]:

- Training and coaching: breaking instruction into steps and reinforcing progress
- Lecturing and explaining: conveying information and ideas so they can be understood and remembered

- Inquiry and discovery: stimulating critical and creative thinking, problem solving, and reasoning
- Groups and teams: facilitating learning through group activities and team projects
- Experience and reflection: drawing learning from the practical experience gained from participating in the project

The effect of assigning cadets to small teams with dedicated faculty mentors is that this approach requires a substantial commitment from the faculty to work closely with the students and with each other. The need for strong communication and integration across all the faculty members on the project is one of the primary challenges we face in executing the program.

IV. Conclusion

Our experiences with developing an undergraduate curriculum for small satellite design point out some of the unique opportunities and pitfalls of implementing an ambitious interdisciplinary program. Our program at the Air Force Academy includes a combination of military, academic, and commercial participants, similar to the large-scale DoD programs our graduates will encounter as active-duty officers. This first-hand experience of “learning space by doing space” presents our students with both the subject of their design and dictates a design process consistent with Air Force acquisition and development programs. As Davis notes, “All courses function at two levels: a content level, …the ‘subject’, and a process level, which has to do with the kind of learning taking place and the way that learning is occurring.”[4] The creative process of technology development, encompassing the application of science, engineering, and organization management enhances learning outcomes associated with both the process and content of sound engineering practice.

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[1] Pool, Robert. *Beyond Engineering: How Society Shapes Technology*. New York: Oxford University Press (1997), p. *ix*.

[2] Caylor, Michael J. “Background Paper on the USAFA Small Satellite Program,” USAF Academy Internal Staff Memo, 22 September 1997.

[3] URL: http://www.vs.afrl.af.mil/VSD/TechSat21/

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