GC 2012-5617: DESIGN, BUILD, AND TEST OF ENGINEERING DEVELOPMENT SPACECRAFT HARDWARE IN A SATELLITE DESIGN COURSE AT THE AIR FORCE INSTITUTE OF TECHNOLOGY

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Design, Build, and Test of Engineering Development Unit CubeSats for Satellite Design Courses

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Abstract

Over the last four years, Air Force Institute of Technology (AFIT) students have been provided a hardware intensive satellite design, build, and test course sequence. Over a twenty-week period each year, these AFIT students define system requirements for their assigned mission, design a satellite that can achieve the mission objectives, and build an engineering development unit (EDU) model of their satellite design. Finally, the EDU model's performance is evaluated by the students in a thermal vacuum chamber, which simulates on orbit temperature and vacuum conditions, and on a vibration table, which simulates launch conditions. In this study, we evaluate the concept of modifying this hardware intensive graduate course so that it can be implemented at the undergraduate level. To serve as an example for this study, researchers at AFIT and the United States Air Force Academy (USAFA) are evaluating the possibility of incorporating AFIT's design/build sequence into USAFA's undergraduate astronautical engineering curriculum. The proposed hardware-based curriculum would provide juniors at USAFA with the opportunity to get more hands-on satellite design, build, and test experience using CubeSats developed at AFIT. In comparison, USAFA currently provides their juniors a hands-on experience during a two-day lab with a pre-fabricated satellite kit. This paper evaluates curriculum changes that would allow undergraduate students the opportunity to create, test, and learn from their own satellite designs and evaluates the groundwork for the development of this labor intensive and challenging curriculum at the undergraduate level.

Key words: Satellite Design, Hands-on Curriculum, Hardware Build and Test

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Introduction:

The Air Force (AF) is committed to training and education programs. This is especially evident when the time and money spent on pilot training is considered. Over an estimated $1 million is spent training a new fighter or bomber pilot over the course of 2 years of training. The extensive training is provided to ensure AF pilots are capable of completing important missions without risk to life, limb, or aircraft. AF engineers also need adequate training to perform their jobs. It is common for AF engineers to manage multi-million dollar programs where their required post-baccalaureate training can be as short as a three week course on project management. The astronautical engineering programs at AFIT and USAFA work to enrich that training through undergraduate and graduate programs for AF engineers who complete these respective programs. To maintain space dominance, it is critical that engineers understand what the people they are managing do.

Engineering and science curriculum, at both the undergraduate and graduate level, often incorporates hands-on laboratory experiences. This hands-on lab work provides students with concept relevancy, integrated knowledge, and technical skill required in engineering jobs [1]. Hands-on and project based curriculum are examples of inductive learning techniques where inductive learning reverses the traditional method of deductive learning. In deductive learning, a theory is presented to students and examples are then given in illustrations, in-class experiments or homework exercises. In inductive learning, the process begins with a set of objectives or a problem to be solved. Faculty guides students along the way and the students reach an understanding of concepts through the learning process. Inductive learning allows the student to discover why the material is important and useful [2]. People are motivated to learn things they perceive as something they need to know [3]. Student buy-in and motivation is also enhanced when hands-on active learning opportunities are provided [4]. This method of teaching provides context and relevancy to the curriculum [5].

This inductive learning process is adopted by AFIT and USAFA astronautical and space systems engineering professors who provide their students with clear design objectives and allow the students the opportunity to solve many of the challenges of satellite design, build, and test. This paper evaluates curriculum changes that would allow undergraduate students an increased opportunity to create, test, and learn from their own satellite designs and evaluate the groundwork for the development of this labor-intensive and challenging curriculum at the undergraduate level. Next, we will first discuss the AFIT's CubeSat and then USAFA's FalconSAT satellite design, build, and test educational efforts followed by an analysis of incorporating AFIT's CubeSats into USAFA's junior-level coursework.

Description of Current Programs:

AFIT

The Air Force Institute of Technology (AFIT) serves the AF as its internal graduate institution for engineering, applied sciences, and select areas of management. AFIT provides graduate and professional continuing education and research for the US Department of Defense (DoD). AFIT's Department of Aeronautics and Astronautics provides its graduate students a satellite design, build, and test course sequence. Predominantly, the students who take the sequence have an undergraduate engineering degree and hold positions in space-related fields after graduation.

The primary objective for the satellite design, build, and test course is to allow graduate students the opportunity to design and build a satellite for a specific DoD mission. Not only do the student teams produce a detailed design they are also required to explain and defend their design choices. Each student on a design team generally focuses on a particular spacecraft subsystem. The sequence gives the students exposure to and practice with the software tools and laboratory equipment they may be using for their respective thesis projects. Having each student involved in the element of design they are interested in along with the 30 weeks dedicated to the project allows for a depth and detail that would be difficult to achieve at the undergraduate level.

This satellite design, build, and test course sequence is an optional sequence offered for credit towards a master's degree, typically in astronautical engineering, systems engineering, or graduate space systems. The sequence consists of three 10 week classes. The first class focuses on systems engineering for space systems. The second class focuses on an actual satellite mission design and lab equipment familiarization. The third class focuses on the building and space qualifying of the satellite. In order to maintain low costs and a constrained design environment, AFIT students design CubeSats.

A CubeSat is an industry standard size of satellite and each unit is a 10 x 10 x 10 cm^3 satellite that weighs approximately 1.33 kg. A 3U CubeSat is three units stacked together so it is 10 x 10 x 34 cm^3 and weighs approximately 4 kg [6]. The CubeSat concept came out of a need to accelerate space opportunities and lower the cost for space experiment platforms. The platform development challenge was taken on by several universities [7]. In 1999, Stanford and California Polytechnic State University (Cal Poly) created the prototype that became the standard [7]. Cal Poly also created an interface for CubeSats and launch vehicles, called the Poly-PicoSatellite Orbital Deployer (P-POD). All CubeSats that fly using the P-POD must adhere to the criteria outlined in the "CubeSat Design Specication" document created by Cal Poly [6].

CubeSats have served as an educational tool in many undergraduate and graduate aerospace curriculums throughout the world. Country participants include the US, Japan, Germany, Denmark, Romania, England, Spain, Turkey, Norway, Netherlands, Italy, Switzerland, France, Poland, Belgium, South Korea, Canada, and Columbia [8]. Columbia's first satellite was a CubeSat that played the first stanza of the Columbian National Anthem [8]. Many of the missions perform initial testing on new satellite products. Some missions utilize the CubeSat to perform biological space experiments on bacteria or yeast [8]. Many CubeSat missions have had simple imaging platforms on board. NASA recognizes the academic importance of these CubeSat programs and created an initiative to provide launch opportunities for CubeSats called ELaNa (Education Launch of Nanosatellites) [9].

Developing a space-worthy CubeSat is expensive, typically more than several hundred thousand dollars, and very time consuming, commonly more than two years. In order to provide an educational opportunity at a relatively low cost, AFIT student create engineering development unit (EDU) CubeSats that are non-flight models that use predominantly low-cost components easily found in electronics stores on the internet. However, these CubeSats are designed for a space mission of interest to the DoD which provides sponsors a very realistic evaluation of the DoD sponsor's proposed concepts. As part of the AFIT's satellite design, build, and test sequence, the mission objectives and requirements are given to a team of 6-8 graduate students. From these mission objectives, the students create hardware and software that will lead to a successful mission.

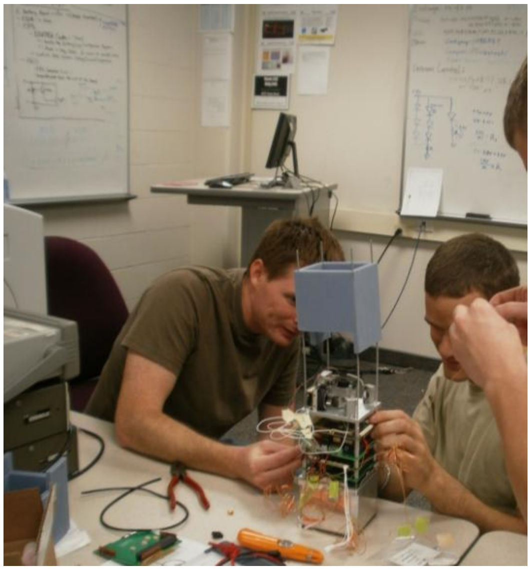

Figure 1: AFIT Students Assembling the EDU CubeSAT

The primary resources for the AFIT CubeSat classes are the course text, Space Mission Analysis and Design, and lectures given by teachers and experts in various space associated fields [10]. Designing for space presents many unique challenges. Some of the space environment considerations for low Earth orbit (LEO) include: free fall motion, vacuum, thermal extremes, solar events, atomic oxygen, space debris, and radiation. Spacecraft must provide their own power, attitude determination and pointing, communication and data handling, and thermal control. The students are free to organize their group as they see fit, but typically each person on the team takes control of the design of one of the subsystems.

The two primary constraints on all the different subsystems are weight and volume. A CubeSat is about the size of shoebox and typically half of that space is reserved for the payload. The attitude determination and control system uses approximately ¾ of a CubeSat unit. This leaves only ¾ of a unit for the power, communication and data handling, and thermal subsystems, if required. Schedule and cost are also limiting constraints on the spacecraft design and are carefully considered.

Throughout the courses there are a few homework assignments and a test to ensure that even though the students specialize in the subsystem they are in charge of for their project they at least have an understanding of the other subsystem design characteristics. At the end of the course, the students produce a detailed final report and a presentation. The final report includes a feasible design of the flight-ready CubeSat, as well as a concept of operations while on orbit, risk consideration, cost, and schedule details. Interested space experts from the local area, other universities, and the DoD attend the final presentation and provide invaluable real-world feedback for the students' design.

After the 10 week design course is complete, the students begin the second class in the sequence where the students build and test and EDU model of the CubeSat they designed in the previous course. An EDU version is a simplified model of the real project built as a low cost effort to reduce risk. The students gain experience in many different technical aspects of actually building a satellite. The students create detailed Computer Aided Design (CAD) models of the structure that eventually gets built in a machine shop. The students solder the various electrical components to the boards that they have a hand in designing. They create software for the spacecraft and ground station. The spacecraft bus always builds upon past classes bus completion. The payloads are new each year and are typically built from scratch.

After completing the hardware build of the EDU CubeSat, the students test it to ensure mechanically it meets standards. The mass moments of inertia and center of mass are measured accurately with lab equipment. The CubeSat then goes through testing to ensure that it could survive both the launch and space environment. An initial functional test sets the baseline for the EDU spacecrafts capabilities. The CubeSats are then put into a thermal vacuum chamber. The chamber at AFIT is capable of creating an atmospheric pressure below 5×10^{-4} Torr. Once the vacuum level is achieved, the chamber is thermally cycled so as to simulate the eclipse and full sun environments the CubeSat would be exposed to during its orbit around the Earth. The CubeSat's are cold soaked to a temperature of -20°C and then heat soaked to a temperature of 40°C. Throughout this thermal cycle, which takes over 8 hours, students continually perform functional checks making sure that the satellite survives the thermal and vacuum extremes.

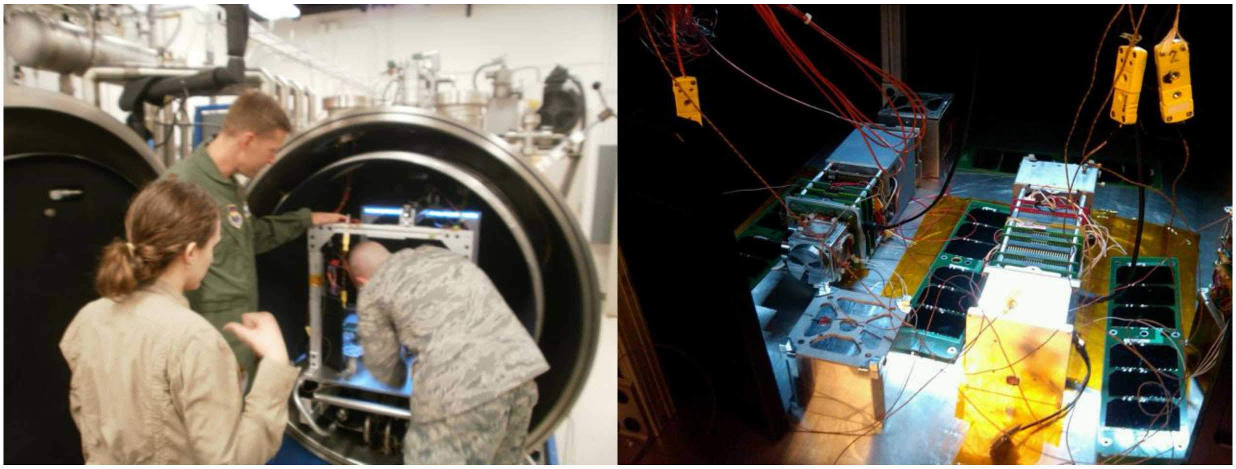

Figure 2: AFIT's Thermal Vacuum Chamber (Left) and CubeSATs Inside (Right)

Once this test is complete the satellite is attached to a vibration table. During launch, the satellite will be exposed to an intense vibration environment and will likely experience multiple g loadings. Testing the satellite on a vibration table helps validate that the satellite is capable of surviving launch.

Upon completion of the 10 week build and test course, the teams write a detailed paper documenting the building process, any design changes that had to be made, and the results of the various test. They also present all results at the end of the course to a panel space experts who provide invaluable feedback. The culmination of this 20 week project provides students with the experience of going through the entire design, build, and test phases of a spacecraft's lifecycle. This is an experience they are very likely use in their future. The final products also provide a relatively low-cost and detailed look at the feasibility of the spacecraft mission in the original proposal.

USAFA

The United States Air Force Academy (USAFA) has a satellite program but it is on a larger scale and has been in operation much longer than AFIT's program. USAFA offers a four-year program of instruction for its astronautical engineers which results in a Bachelor of Science degree in Astronautical Engineering and a commission as a second lieutenant in the Air Force.

The astronautical engineering department at USAFA operates an undergraduate satellite development program called FalconSAT. FalconSAT research is conducted within the Academy's Space Systems Research Center. The SSRC coordinates research funding with outside organizations and provides planning and management for satellite missions. FalconSAT is a senior capstone course that all astronautical engineering majors are required to participate in. The goal of the program is for cadets to 'learn space by doing space.' Seniors and faculty from other departments including management, physics, electrical engineering, computer engineering, and mechanical engineering also participate in the program. The more recent satellites built by the SSRC are Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class, approximately 0.6 x 0.6 x 0.96 m^3 and 180 kg. The FalconSAT program had its first success with Falcon Gold in 1997. Falcon Gold's mission was to investigate the feasibility of performing GPS-aided navigation by satellites operating above the GPS satellite constellation. Currently, the program maintains communication with FalconSAT-3 and recently launched FalconSAT-5. Both of those satellites have propulsion experiments as their primary payload.

Figure 3: FalconSAT 5 in Clean Room [11]

The process to take the satellite from the initial design to launch takes between 4 and 5 years. Each year the senior cadets participate in the phase of the mission that is currently being worked on in the FalconSAT program. Typically, cadets only see one of the phases that include system design, EDU fabrication, qualification model fabrication and testing, flight vehicle fabrication, flight qualification testing, launch vehicle integration, launch site operations, or mission operations.

The cadets gain hands-on experience with a satellite that has real mission objectives. Cadets take the mission objectives and define hardware requirements. They do a complete paper design of the satellite and conduct design reviews for the benefit of the customer. They build three or four versions of the satellite over the 4-5 year program. They typically build a mass model, an engineering development model, a qualification model, and a flight model. The mass model helps with one of the hardest design challenges for satellites which is keeping the spacecraft light, but rigid and fitting all the payloads into the designated volume. The EDU model allows the SSRC the opportunity to resolve many of the engineering, hardware, and software challenges. The qualification model is very similar to the flight model. The qualification model is created so that robust space and launch environment testing can be done without harming the flight model. The flight model only undergoes flight qualification testing which is specified by the launch provider. The cadets then participate in all the organization of manifesting a launch. Once the satellite is launched, the SSRC maintains a ground station capable of communicating with any and all of the FalconSATs. Cadets carry out spacecraft flight mission objectives by sending commands from the ground station.

The FalconSAT program directly involves cadets in all the stages of spacecraft design and development. The faculty provides the continuity for the multiple year program. For the FalconSAT program to be successful, cadets must have adequate technical knowledge and practical hardware experience before working on the program.

The primary preparatory class for the FalconSAT capstone project is taken by junior cadets at the Academy. The course is an overview of the spacecraft design, build, test, launch integration, and mission operations processes, also following the same course text that AFIT uses, SMAD. The course objective is to introduce the undergraduate to the satellite development process itself and the tools used therein. Students learn about the design of each satellite subsystem and the overall satellite program from cradle to grave. With this breadth of material and the limited lecture time, only 40 hours, there is not time for the students to do detailed design and analysis. The course is primarily lecture based. There are a few labs mixed in with the course material. There is a basic soldering lab and a couple labs with a pre-fabricated simple small satellite called EyasSAT. EyasSAT is a robust demonstration satellite designed for classroom use and has all the basic subsystems of a typical satellite bus. EyasSAT is accompanied by a professionally developed curriculum [12]. EyasSAT provides a great introduction to basic satellite functionality.

Figure 4: USAFA Student Working on EyasSAT [13]

Incorporating AFIT's CubeSats into the undergraduate course would introduce real-world relevance to the satellite design process. Each CubeSat has a unique mission that can be used as the course example. The CubeSat hardware can be given to the students for space qualification testing. This adjustment to the current course curriculum is explained and evaluated in the next section.

Proposed Changes:

For USAFA to successfully take over the fabrication and space qualification testing of the AFIT CubeSat, they will need to stay involved in AFIT's current CubeSat development processes. Over the course of the next several years, AFIT will provide USAFA with their latest CubeSat designs so USAFA faculty and staff can be familiarized with the equipment and protocol standards. USAFA will also need to have some laboratory space for the junior-level course. The cadets will need a workplace, access to tools, and soldering equipment. They will also need to provide the juniors access to the TVac and vibration test equipment so they could conduct thermal vacuum and vibration testing at USAFA. The CubeSat design will have to be well documented down to the component level for USAFA to take over the project with ease. AFIT's CubeSat bus design will provide cadets with the opportunity to have hands on experience with the fabrication and testing portion of a satellite's lifecycle before they enter the senior capstone course.

In the course, the cadets would experience a large portion of the satellite mission lifecycle with a hands-on project in the time span of a semester using current lab equipment at USAFA and the AFIT CubeSat design. The cadets would be able to fabricate the CubeSat and evaluate its performance in space qualifying tests.

Predicted Outcomes

Incorporating AFIT's CubeSat bus likely will have three beneficial outcomes of note. The first is that AFIT will be able to free itself from CubeSat bus design and dedicate that research energy and time to payloads. CubeSat bus design and fabrication has been done in industry and many undergraduate institutions so there is already a model in place. The undergraduate challenge is to understand and become familiarized with the satellite design process and challenges. The graduate level challenges lie in the new science, experiments, and missions of the payloads.

Each payload is unique and investigates a new scientific question or space mission challenge. Wrestling with problems that do not have a pre-formulated solution are the expected types of research graduate students at AFIT are eager to tackle.

Building satellites and conducting space qualification testing on FalconSAT-class satellites consumes at least three years of the 4-5 year lifecycle that the SSRC goes through for their small-satellite capstone class. If the junior level preparatory class provided cadets with the experience of building and testing CubeSats, the cadets would have the necessary technical and laboratory skills it takes to have a successful FalconSAT. The opportunity to work on real spacecraft hardware before contributing to the FalconSAT program would also give cadets valuable insight and knowledge about all the components necessary to complete a basic mission. This knowledge will allow the cadets to more fully understand the spacecraft subsystems and the experience will give them a leg up on the design process.

Cubesats provide a relevant platform that many Air Force officers will see in their operational careers. Experience with a typical space-flight worthy system is critical to the training of these future acquisitions officers. While kits may be available that can replicate the experience of qualifiying hardware, those kits do not result in an operational mission. These cubesats, at the undergraduate and graduate level, deliver the same sense of urgency and care as any developmental space mission that these officers will encounter. To believe that a kit could be used instead of real hardware is akin to believing that remote control planes or simulators would be appropriate to train a pilot. This is similar to believing that being in simulated combat is similar to actual combat. While the experiences may be similar, there are very real differences and consequences. In engineering, as with other disciplines, there is no substitute for real hardware with a real schedule to perform a real mission. Anything else is purely academic and not “real world.”

The cooperation between USAFA and AFIT to produce CubeSats would provide the DoD with a relatively low-cost option for CubeSat missions. Since the labor for designing, building, and testing the CubeSat will be mainly student labor the cost for manufacturing a CubeSat is relatively low. This real-world value for the DoD also increases student buy in to the program. Being able to work on a real mission is exciting for students but also provides insight into actual space program experience. Many issues like funding and changing customer requirements present themselves when working on real missions.

Combining the efforts on CubeSats at AFIT and USAFA will provide real-world value to the DoD space mission as well as give cadets and graduate students an invaluable hands-on active learning experience.

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