AC 2012-3199: SPACECRAFT INTEGRATION AND TEST: AN UNDERGRADUATE COURSE IN SYSTEMS ENGINEERING PRACTICE

Dr. Michael Swartwout, Saint Louis University

Michael Swartwout is an Assistant Professor in aerospace and mechanical engineering at Parks College, Saint Louis University. He earned his Ph.D. in aeronautics and astronautics from Stanford University. As a graduate student, he led the development of the student-built satellite, Sapphire, which was launched in 2001. Starting at Washington University in St. Louis and continuing at Parks, Swartwout has been involved in four student missions on the space shuttle and numerous balloon-launched student experiments, as well as flights on NASA's Microgravity University. His student teams have been in five consecutive Air Force University Nanosat competitions, taking second place three times. Their next student satellite, COPPER, is slated to launch in June 2012 as part of NASA's ELANA-IV flight. Swartwout's research interests center on the design and operation of low-cost space systems.

Dr. Sanjay Jayaram, Saint Louis University

Sanjay Jayaram is an Associate Professor in the Aerospace and Mechanical Engineering Department of Saint Louis University. He obtained his Ph.D. degree in the area of mechanical engineering from University of Central Florida in 2004. He teaches control systems/mechatronics, space systems engineering and astronautics related courses as well as engineering sciences courses. He has published several peer reviewed journal and conference papers in these areas. His research areas are space systems, robust fault tolerant control, nonlinear control, adaptive control, small spacecraft design, high performance spacecraft components, mechatronics, real-time health monitoring, and diagnostic methodology.

Spacecraft Integration & Test:
An undergraduate course in systems engineering practice

Abstract- The teaching of good systems engineering practice to undergraduates requires that students gain experience with real, complex systems. We have created a candidate course that blends the theoretical principles of spacecraft integration & test with the practical constraints of preparing a small student-built spacecraft for launch. We introduce four heuristics of spacecraft I&T that explain why certain processes are used in major environmental and functional testing, and also justify the development of massive systems for documentation. In parallel with the theoretical work, students are responsible for designing, conducting and analyzing spacecraft acceptance tests for a small satellite, and preparing the test reports for evaluation by NASA. NASA's Educational Launch of Nanosatelllites (ELaNa) program appears to be an ideal platform for improving space systems education. As will be discussed in the paper, this approach had benefits associated with real-world experience and student motivation, but also brought significant drawbacks when the launch schedule slipped by nine months.

1 Introduction

Modern aerospace systems can be quite complex, with hundreds or thousands of electrical, mechanical and chemical elements working together to achieve a challenging objective. In fact, these systems are complex <u>because</u> of their challenging objectives: aircraft and spacecraft must transport people, cargo and time-sensitive data through extreme environments and do so with very high reliability. Simple solutions are often insufficient, and yet the complex solutions require years of development and tens of millions of dollars (or more) – and still run a high risk of failure.

In the design and fabrication of aerospace vehicles, the role of the systems engineer is to ensure that a vehicle is created that meets the mission objectives within the constraints of cost, schedule and risk. Good systems engineers bring great value to their organizations, but universities are not yet producing good systems engineers.[1,2] Many schools offer graduate-level programs in systems engineering, which focus on computational tools and management strategies. These tools are essential to the role, but the tools are only one aspect of the job. Moreover, the authors believe that undergraduates can and should receive better training in the core principles of systems engineering.

The challenge with teaching the “core principles” is that professional engineers usually acquire this knowledge through experience, the painful learning from failures and, occasionally, successes. In fact, while he was NASA Administrator, Mike Griffin flatly stated that universities were not equipped to teach systems engineering, and that students should enter the workforce as soon as possible in order to learn to become good systems engineers.[3] One of the cited benefits of the Air Force-sponsored University Nanosat spacecraft competition is that it gives students the chance to “fail” on their own, student-built satellites, and thus spare their future employers from having them learn the lesson on the job.[1] We applaud the University Nanosat Program’s approach; we want to formally integrate it into the curriculum at our university.

Therefore, our objective was to create an upper-level undergraduate elective course in systems engineering that could give students practical experience through classroom learning and hands-on activities. We chose the focus of this course to be spacecraft integration and test (I&T) to complement our existing courses in spacecraft design and failure analysis, and because we had an immediate need to train students in I&T for our own student-built satellite.

In the spacecraft development process, Integration and Test is the last stage before launch; it consists of the steps necessary to convert a paper design into a functional, flight-ready spacecraft. The **Integration** phase covers the purchase, fabrication and assembly of spacecraft components into subsystems and then the completed spacecraft. Due to the number of steps involved, integration can take months to accomplish.

The **Testing** phase (often called Verification) consists of all activities necessary to prove that the spacecraft will achieve its objectives. Testing covers a range of functions, including environmental testing to prove that the vehicle can handle the harsh environments of launch and space operations, functional tests to show that the components can operate together as planned, and the documentation trail necessary to show that every circuit, wire, nut and bolt is of a material compatible with space flight and has been assembled using proper procedures. (Several spacecraft have been lost because their materials evaporated or oxidized in orbit, or because the electronics failed due to static charging or high-gradient electric fields.)

Integration and Testing functions often take place in parallel or cyclically; a component may be assembled and put through an initial vacuum checkout before being integrated into the entire spacecraft. Therefore, I&T is usually treated as one extended phase. For large modern spacecraft, I&T can take anywhere from 10 months to 5 years. In the case of very large systems such as the Webb telescope, technical challenges that crop up in I&T can extend the phase well beyond 5 years.

In Fall 2011, we offered the first course: Integration & Test of Space Systems with an enrollment of nine undergraduates. In this paper, we will provide an overview of the objectives, syllabus and assessment of this course in spacecraft integration & test. We will place this course in the context of aerospace engineering at our university and our other systems-engineering courses and introduce the hands-on work done through the Research Laboratory and the COPPER satellite. We will assess the results of the first course and provide lessons learned and future work.

Our first offering had mixed results; in addition to the typical mid-course corrections that take place with any new technical elective, we were beset with challenges external to the course. Some of those challenges were home-grown (e.g., our testing facilities) and some were outside our control – most notably, the nine-month delay in our NASA-sponsored launch. While launch delays are a typical part of aerospace programs and worth incorporating into the class, the magnitude of the delay was a significant challenge. We will offer suggestions on how to manage those in the context of the class.

2 Space Systems Education at Our University

Our university offers accredited undergraduate degrees in aerospace engineering (AE) and mechanical engineering (ME) through a combined AE/ME department. AE and ME students are required to take a number of technical electives. Like most undergraduate AE degrees in the country, our program emphasizes the aviation side of AE. However, there is a core group of faculty with an interest in spacecraft systems, and with college/department support, they have created a four-course offering. All students interested in the sequence must take the first course, below, and have the opportunity to follow up with one (or more) of the other classes.

- **Space Systems Design & Analysis** is the first course in the sequence. It covers the overall spacecraft design process, the requirements flowdown, subsystem sizing and "Phase A" designs. All AE students take Astrodynamics in their junior year, so the orbital mechanics in this course is focused on Earth-orbiting mission design. This course is used to prepare seniors for their capstone design. It is offered every year.
- **Space Mission Failures** was created in Spring 2011 to study the systems engineering process through failure analysis. It consists of a series of case studies in mission failures. (A paper on this course is also being presented in this conference.) It will typically be offered every other year.
- **Integration and Test of Space Systems** is the course described in this paper. Depending on our final assessment and laboratory needs, it may be offered every year.
- **Advanced Space Mission Design** gives the instructors and students the opportunity to study a new technology or mission concept in great detail. (At a previous institution, one author covered topics such as solar sails and fractionation.) It is offered only according the research/teaching needs of the faculty and student interests.

2.1 Space Systems Research Laboratory (SSRL)

The Space Systems Research Laboratory is led by one author; the affiliated faculty include the other author and faculty of the Electrical Engineering department. SSRL has a research focus on the design, fabrication and operation of low-cost spacecraft architectures and technologies. SSRL faculty were involved in the design, fabrication and launch of the Sapphire satellite,[4] several Shuttle payloads, and University Nanosat missions at three schools.

SSRL hosts the fabrication, testing and operations equipment used in this course: a vacuum chamber with heat lamps, a CubeSat-scale vibration table, an OSCAR-class ground station, and all the electronics design, assembly and test equipment. Machine shop needs are met by the College's facilities.

2.2 COPPER

The Close-Orbiting Propellant Plume and Elemental Recognition (COPPER) mission will be our first satellite. It has been selected to fly as part of NASA's Educational Launch of Nanosatellites (ELaNa) program; ELaNa-IV will carry nine CubeSat-class spacecraft on a SpaceX Falcon 9 launch. The CRS-2 launch is currently earmarked for 8 December 2012; SLU is required to deliver a fully tested, flight-ready spacecraft by 1 September 2012. CRS-2 will eject its CubeSats at nominally 325 km altitude before continuing on to deliver cargo to the International Space Station. The estimated orbital lifetime is 60 days.

COPPER's primary mission is to flight test a new compact infrared imager. The FLIR Tau microbolometer array (Figure 1) was designed for challenging air and land applications; the COPPER team will fly an unmodified Tau in a 1.3 kg CubeSat. While the main application will be using the Tau to capture thermal images of land and ocean at 600 meter resolution, the COPPER team is working with SpaceX to secure permission to capture video of the post-separation sequence; we believe that any upper-stage engine firings will be visible in the 6-12 micron spectrum as the hydrazine plume interacts with the plasma bubble surrounding the stage. COPPER's primary payload interfaces with the spacecraft bus via an in-house FPGA-based system; the FPGA is capable of keeping up with the Tau's 30 fps, 320x240 pixel, 14-bit images and storing the video frames locally. When called on by the spacecraft CPU, images are transferred serially to the bus for immediate downlink.

COPPER's secondary mission is to provide a functional orbital checkout of a new radiation-effects modeling payload developed by another university.[5] The Commodore payload will monitor modern SRAM devices for radiation-induced events to calibrate new predictive models. Commodore is a precursor to Independence; this more complex radiation-effects modeling payload will fly on our Argus satellite, nominally in 2013.

Figure 1. FLIR Tau [courtesy FLIR]

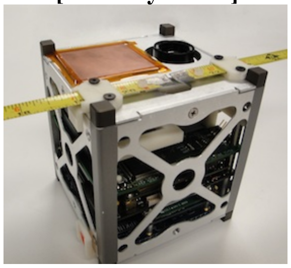

Figure 3. COPPER Engineering Model

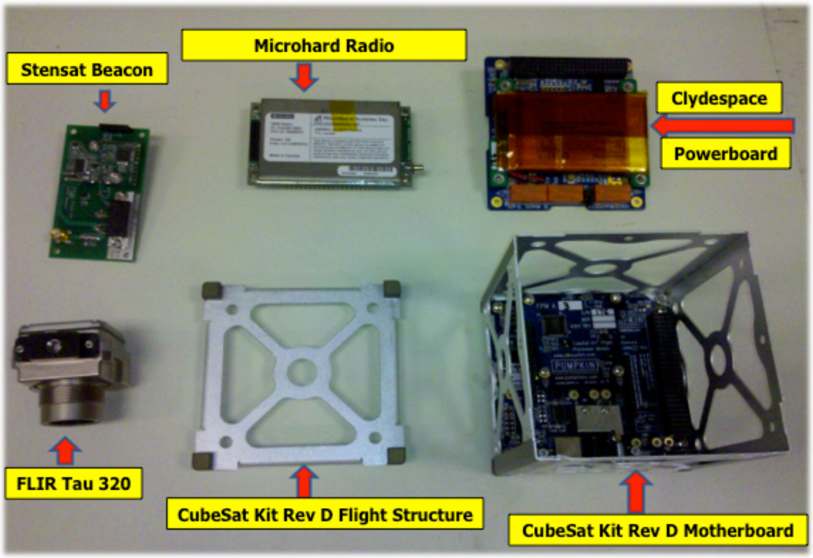

Figure 2. COPPER Components

As shown in Figures 2 and 3, COPPER consists of a stack of commercially-available CubeSat-class subsystems in a 1U aluminum frame: the PIC24-based CubeSat Kit processor runs the Pumpkin SALVO Real-Time Operating System. The Clyde Space Electrical Power System provides regulated 3.3 Volt and 5 Volt power to the spacecraft, supplied by body-mounted solar arrays and a lithium ion battery (1.5 W nominal average daily power). The Microhard MHX2420 transceiver broadcasts data in the unlicensed 2 GHz band, backed up by a Stensat 1200 baud beacon. The student-built FPGA board interfaces with the Tau, and is stacked with the other electronics. COPPER is passively oriented with permanent magnets to provide best orientation for imaging and downlink relative to North America.

When we opened the course for registration (late Spring 2011), COPPER was to launch in March 2012, requiring a NASA acceptance review to take place in November 2011 and a spacecraft delivery to NASA in December 2011. Therefore, students in our I&T course would have the practical responsibility of helping the COPPER team develop the verification documents required by NASA and presenting them to NASA at the acceptance review. By the first day of class in August, the launch date had slipped to June 2012, requiring an acceptance review in February 2012. Before midterms (October 2011), the launch date had slipped six months more, to December 2012, only to slip again in February 20120, finally (?) stopping at Summer 2013. (Cross your fingers that it stops there.) Obviously, these slips had a significant impact on the way we conducted the course, and we will discuss the implications, below.

3 Course Overview

3.1 Outcomes

Our syllabus reads as follows:

> Before a complex system such as a spacecraft is allowed to enter service, it must first undergo a thorough checkout. These vehicles are extremely expensive and must operate in the extremely harsh environment of space. Due to the complexity of the spacecraft, various components may interact with one another in unexpected ways. Therefore, the space industry has developed a formal process for integration (assembly of the spacecraft) and test (verifying that the spacecraft will function as intended in the space environment). In this course, students will learn the theory and practice of spacecraft integration & test, and apply it to space systems in development at our university. Modern tools and practices (i.e., CubeSats and Operationally Responsive Space) will be introduced as well.

We identified six outcomes:

1. Ability to define the necessary steps in the spacecraft integration & test sequence and justify their inclusion.
2. Ability to develop spacecraft test plans that trace back to mission requirements.
3. Ability to execute the following spacecraft test plans and analyze the results: functional checkout, vacuum testing, thermal cycling and vibration qualification.
4. Ability to optimize project schedules in the presence of competing goals of cost, performance and deadlines.
5. Ability to create and present verification reports according to NASA/Air Force standards.
6. Ability to work in multidisciplinary teams.

In order to achieve those outcomes, we covered ten subjects in class:

1. Spacecraft Design Lifecycle
2. Requirements Flowdown
3. Requirements Verification – Theories (or lack thereof) and Approaches
4. Spacecraft Documentation and Version Control
5. Spacecraft Assembly – Standards and Practices
6. Ground Support Equipment

7. Functional Testing
8. Environmental Testing: Vibration
9. Environmental Testing: Thermal Cycling
10. Environmental Testing: Thermal Vacuum

Each subject was covered in two ways: as a generic topic using NASA and industry examples, and then specifically adapted to the COPPER spacecraft. For example, we introduced Requirements Verification using the topics covered in Wertz's Space Mission Analysis & Design (SMAD), then the students were tasked with creating a verification document based on the ELaNa-IV Interface Control Document (ICD).

3.2 Governing Principles

Because of scheduling constraints, we chose to allow students to register for I&T without having our Space Systems course. (In hindsight, we probably will not allow that again.) Since a classroom version of Integration & Test could be both very dry and very overwhelming for students with little to no space background, we sought to identify simple themes that encapsulate the I&T process. The purposes of these themes were to provide context for the spacecraft development process, to help students achieve outcomes 1, 2 and 4, and to stimulate discussion. In consulting with alumni, industry collaborators and instructors at other universities, we identified four heuristics of spacecraft I&T. These were intentionally defined in exaggerated terms in order to encourage students to challenge their premises. The four themes are:

1. **Physics Is Actively Opposed to Space Flight**. Ground, launch and space environments are unforgiving, and thus spacecraft are prone to failure. The physics of achieving orbit are so challenging to overcome, that small deviations from nominal functions result in catastrophic failure. The consequence of this principle is that expensive, high-performance, complex systems are usually required to achieve results in space.
2. **Nothing Ever Works the First Time You Put It Together**. Complex systems have so many failure modes, and complex systems have so many complex interactions that it is impossible to predict all possible failures. By contrast, it is easy to overlook some small factor that makes two parts incompatible. Systems engineers must account for complexity when designing spacecraft and when planning the integration & test process.
3. **There is Never Enough Time Or Money**. Space systems have limited budgets and limited schedules. Due to the stringent performance requirements, harsh environment of launch & space, it is physically impossible to comprehensively test all possible scenarios before launch. Systems engineers must prioritize their tests to resolve the most significant risks.
4. **Fear Rules All Decisions**. The natural – perhaps even rational – approach when developing high-value, complex systems that must operate in harsh environments is to limit uncertainty. Building new systems that duplicate (or strongly imitate) previous systems is one approach to solving the performance problem while satisfying the cost and schedule constraints. This naturally leads to a fear (or healthy skepticism) of new technologies and new design paradigms; new systems have not been proven, and thus their failure modes are unknown. We encourage our students to use this fear instinct to

develop good processes: in the light of limited cost and schedule, focus testing resources on the parts of the spacecraft most likely to fail.

3.3 Assessment Methods

Originally, we had intended three types of assessment: two student-based assessments (self-assessment through surveys and a peer assessment of their work by the rest of the COPPER team); one faculty (graded) assessment of their final reports; and one external assessment via the NASA acceptance review. As noted above, the acceptance review has slipped until September 2012 and thus is not applicable. The other methods were implemented to mixed results as will be discussed, below.

4 Results of First Course (Fall 2011)

Ten students enrolled in the course, and three more participated indirectly via an independent study. The students were mostly juniors and seniors, though three sophomores were allowed to register because of their prior work with COPPER. The students were from aerospace, mechanical and electrical engineering, as well as engineering physics (Outcome 6). The students created a comprehensive test plan to meet NASA's acceptance review requirements (Outcomes 1, 2 and 5) and performed preliminary environmental tests to demonstrate the performance of our test equipment (partial Outcome 3). They also created a risk assessment process (outcome 1). Outcome 4 was addressed at a macro scale because of the effects of NASA's schedule slips on our project, but otherwise could not be directly assessed.

Of the 13 students who completed the course, two have graduated, four are seniors now pursuing a spacecraft project as their capstone design, and three are working directly on the COPPER project. The other four students are not involved with SSRL activities. Student surveys indicate that they were satisfied with the pace and rigor of the course, but were very unsatisfied with the schedule delays. (A sentiment we share.)

As noted above, the primary challenge was our dependence on external resources to complete course objectives. The effect of the schedule slip was immediate and obvious: several students dropped the course in the week following the announced delay, and there was a significant drop in urgency demonstrated among the students who remained.

A second, related challenge was that the I&T students were dependent on the (volunteer) COPPER spacecraft team to provide the finished satellite for testing. As is typical in student (and professional programs), when the launch schedule slipped by nine months, the spacecraft delivery schedule started to slip as well. Furthermore, the COPPER team experienced significant technical challenges in the completion of the FPGA interface to the primary instrument (Heuristic 2), which further pushed back the spacecraft delivery date. Similarly, lacking the urgency to complete the testing equipment, the volunteer team working on the vacuum chamber reduced their efforts.

In retrospect, it was a serious mistake to tie course outcomes to the NASA schedule (and, by extension, to the student-built satellite). As many before us have said, it seemed like a good idea at the time – not only because of the potential synergy between COPPER, NASA and the course, but because the authors have had success tying coursework to student satellite projects in previous years, even when NASA schedules slipped. The difference this time is that 9 of the 13 students to complete the course had not participated in the satellite project before that semester, and thus had a much lower sense of ownership for completing the spacecraft, and much less familiarity with how testing needed to proceed.

On a related note, the second bad decision we made was allowing students to take the I&T class without first taking our Space Systems course. The students who had taken that course were consistently the best prepared in our I&T course and the ones most capable of pursuing independent work; they could plan tests and execute them with much less faculty input. On the other hand, had we only allowed students with the prerequisite to enroll, the class would have been cancelled for insufficient enrollment! Still, we intend to make the Space Systems course a hard requirement in future offerings.

Not all of our decisions were bad, and not all outcomes were disappointing. Students demonstrated great enthusiasm for the material and participated very strongly in discussions. The faculty assessment of their final work (i.e., our grading of their final projects) was very favorable; the students demonstrated an understanding of the key functions of I&T through their verification plans and results (Outcomes 2 and 3). Despite the challenges of using the COPPER spacecraft, it provided much-needed context for the students, providing a concrete example of the general principles involved.

5 Conclusions and Future Work

We believe that the principles of space systems engineering can be taught at the undergraduate level and that spacecraft integration & test phase is an excellent part of the spacecraft development lifecycle for such instruction. However, in order to maximize the successful outcomes, students must have a comprehensive introduction to overall lifecycle and especially subsystem sizing and analysis. This can be accomplished either as a precursor course or by spending the first third to half the semester on the subsystems.

Our "four heuristics of space systems" were a very successful method for engaging the students with the material, and can be applied to other parts of the design lifecycle or to other aspects of engineering. (Students now regularly cite the heuristics to us in other classes and contexts.) We recommend developing similar hyperbolic statements to spur discussion in other subjects.

It is very important to use real hardware for practicing the integration & test steps and for motivating students. However, this approach is fraught with danger should that real spacecraft experience development problems outside your control. It might be preferable to use existing space-like vehicles (such as the EyasSats) or already-completed functional engineering models as practice.

We intend to offer this course again in Fall 2012, in advance of our submission of a spacecraft design to the University Nanosat 7 Final Competition in January 2013. The distinct advantage of that program is that the final competition date is fixed, and will not slip.

6 Acknowledgments

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