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Building Engineers: A 15-Year Case Study in CubeSat Education

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ABSTRACT

The University of Illinois' NanoSatellite Design Course is in its 30th semester of instruction. Since 2001, this pioneering course has strived to use CubeSats as a vehicle for education. During its run, it has provided hundreds of students with hands-on satellite design experience. During the 15 years of operation, the course has undergone a constant metamorphosis. Between incorporating new instructional elements, adapting to new curriculum requirements, and striving towards new mission goals, the course evolved through several incarnations all the while keeping a constant focus on using CubeSats as an educational tool for young engineers.

The NanoSatellite Design Course at the University of Illinois is a one- or two-semester, multi-disciplinary course in the College of Engineering. The course consists of two one-hour sessions per week: one special topic lecture discussing technologies or processes vital to CubeSat design and testing, and one systems meeting for students to discuss their weekly project progress. Outside of the classroom, the students engage in team-based projects to advance the University of Illinois' CubeSat missions which currently include the Illinois CubeSail and the LAICE spacecraft – both missions are manifested for 2017 launches. The students are periodically assessed on their project work through preliminary design reviews, technology demonstrations, and final design reviews. The largest graded component of the course consists of the thorough documentation of their projects in engineering documents (life cycle documents, operator's manuals, testing protocols, etc.). From an instructional perspective, the course straddles the lines between a systems design course and a senior design level project lab, allowing it to serve a variety of functions within the University curriculum.

In this paper, we will present the evolution of this course highlighting the multitude of lessons learned throughout the 15 years of its operation. We identify the variety of tools needed for managing student projects over multiple semesters and even over decades; weighing the value of lecture based and lab based content in student instruction; and examining the how to meld course projects into mission timelines. We will also introduce the two new courses we are currently developing which serve to further educate students through engagement via small satellite research. Our ultimate goal is to present a roadmap to be applied at other universities for the creation and continued execution of curricula that use CubeSats as an instructional tool.

INTRODUCTION

In the fall of 2001, the University of Illinois introduced a special topics course focusing on nanosatellite design. During the past 15 years, the course has undergone a constant metamorphosis while providing instruction to hundreds of students throughout the 30 semesters it has been offered.

The course was conceived as a way to provide students with hands-on experience in systems engineering. This departure from the largely theoretical engineering curriculum would enable students to apply engineering principles in a real-world, interdisciplinary setting. The course was originally devised as a special topics course that could also serve as an interdisciplinary capstone engineering course. Interdisciplinary capstone courses of this type have been demonstrated to improve the quality of solutions created by graduate engineers[1]. Universities around the world have implemented their own versions of nanosatellite design courses with tremendous success[2-5]. These courses have leant tremendous insight into using nanosatellites as an educational platform. We hope to share the insight from our experience.

The course presented a series of lectures on topics relevant to satellite design. Outside of lectures, students would collaborate to design a mission driven satellite: Illinois Observing Nanosatellite (ION) (Figure 1). The group was highly interdisciplinary, with students from Electrical and Aerospace Engineering (the two sponsoring departments) comprising a combined 80% of the enrollment, while the rest of the team comprised of Mechanical Engineering, Computer Science, General Engineering, and Theoretical and Applied Mathematics students.

The mission of ION, a 2U science nanosatellite that would measure airglow emissions from the mesosphere, was chosen with the belief that designing a satellite with a true science mission would inspire students to progress the design. The belief proved true as the class managed to push for a launch in July of 2006. Unfortunately, that launch proved disastrous as ION was lost along with 17 other satellites when the launch vehicle crashed shortly after lift-off.

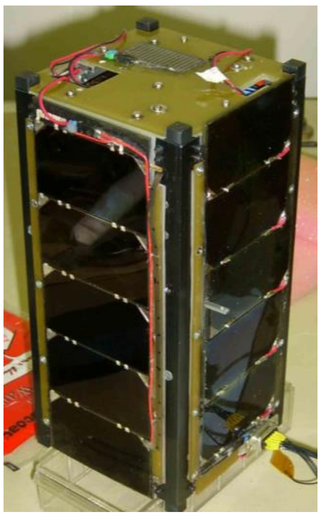

Figure 1: ION, the University of Illinois' first nanosatellite

Redefining the Mission

The course had spent many years building ION, as well as years commissioning a ground station to track it once in orbit. All future planning for the course revolved around having a mission on orbit to track, operate, and study. In the wake of the ION's demise, the course faced a decision: rebuild ION or find another mission. Ultimately, the course elected to follow a third option: design a generic, scalable, satellite bus.

Even in 2006, the number of nanosatellites produced by universities was growing[6]. While ION represented an impressive technological achievement for a university based satellite group, it was far from perfect. The timeline imposed by the launch opportunity resulted in rushed design choices: the satellite required heavy and complicated harnesses to connect the various subsystems; the various communication protocols were difficult to integrate in a single framework; the satellite assembly procedure was unnecessarily complicated making qualification testing challenging. Ultimately, the goal of pushing the ION mission to flight readiness became at odds with the mission of the course: building engineers. The work done on ION was exemplary for university students, but a looming mission would always put pressure on the course. While ION's mission concept would continue to be developed through affiliated research groups, it was decided that the best way forward for the course was to focus on designing a new bus that applied all the lessons learned from its predecessor.

In this paper, we will present the evolution of our course from the fall of 2006 to today, focusing on our current implementation of the course. The information presented is intended to convey the lessons learned from our experience teaching the course, as well as provide a road map for the implementation of similar programming at other institutions.

REDEFINING THE COURSE

Requirements definitions and initial design work for the new satellite bus began in the fall of 2006. By the fall of 2007, the newly dubbed IlliniSat-2 bus was becoming a reality. The new bus architecture would be scalable from 1.5U to 2U, 3U, and eventually 6U. The system would be generic, accommodating a variety of payloads and mission profiles. The system would be easy to test, assemble, and integrate.

Figure 2: Rendering of the IlliniSat-2 bus (3U model shown without payload)

Making a generic, scalable nanosatellite bus was a new challenge for the course. While progress was initially quick, the project became encumbered by the intricacy of ever more complex systems engineering. Additionally, with the miniaturization of hardware opened new avenues previously inaccessible to ION which further altered the concepts from the previous satellite design. While the overarching design was to remain simple, making a robust, generic nanosatellite bus capable of scaling from 1.5U to 6U became too difficult to advance with the existing course framework.

Standing in the way of progressing the IlliniSat-2 bus were two major hurdles: familiarizing students with the satellite bus architecture, and teaching students the requisite skill sets to advance the more sophisticated designs.

Introducing Students to the Bus Architecture

In terms of familiarizing our students with the existing bus architecture, we identified our documentation chain as the principal short coming. Until the Spring of 2007, the vast majority of documentation consisted of end of semester reports. The reports would be original writings detailing the progress made by the team in the semester. They focused almost exclusively on results, and often lacked detail on motivation or method. Moreover, the documentation lacked continuity with previous semesters. In an inspection of previous documentation, it was not uncommon for work to be duplicated experiments from two years prior. In an extreme example, and the same antenna pattern had been characterized three separate times over the period of 5 semesters. Each successive semester compounded the problem as the amount of reports continued to increase and provided less readily interpretable information.

To alleviate this problem, we redefined our documentation requirements. Rather than creating end-of-semester reports, students were required to create proper engineering documentation. The documentation now takes the form of operator's manuals, system lifecycle documents, interface control documents, assembly plans, qualification testing documents, and other engineering documentation. Rather than make new documents every semester, students were tasked with revising older documents if they existed and only creating new documents if one did not exist. This shift enforced continuity by 1) condensing the work on a particular subsystem across several semesters into a single document (or well defined series of documents) and 2) making the current status of a subsystem obvious to all new students. Implementing this change required a substantial time investment in creating templates and examples for the various document types, as well as considerable time condensing the previous semester reports into the new formats.

In order to further facilitate the transference of information across semesters, we organized the information into a project wiki. The wiki allows us to organize the documentation by subsystem. The wiki also provides automatic sub-versioning of documentation which allows us to store outdated copies for reference should we ever need to investigate older design concepts (Figure 3).

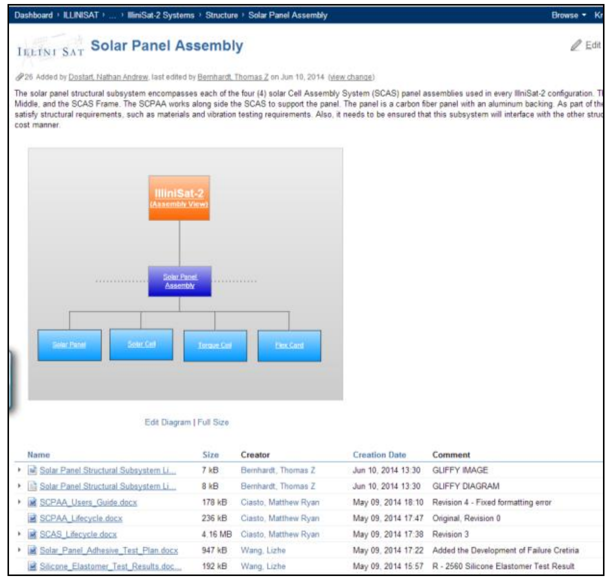

Figure 3: Example page from project wiki.

Teaching Requisite Design Skills

With a better understanding of the bus architecture, we were still faced with the difficulty in building the requisite skills sets. The more advanced designs required students to possess a myriad of skills not currently taught through the existing curriculum. These skills included the ability to create professional engineering drawings, being able to understand geometric dimensioning and tolerances, thermal FEM analysis, high quality electronic CAD layout, functional and environmental testing, among others. In order to teach students these abilities, we had to create a framework to instruct them.

In order to teach these skills, a series of tutorials were introduced to the course. Students were required to attend at least one of the tutorials and encouraged to attend more. The tutorials ranged in quality and suffered from ill-defined learning objectives and extra burden on the instructional staff. After a couple semesters of refinement, the tutorials evolved into what we dubbed the "stream project". The stream project broke the course into two disciplines or streams: Aerospace and Electrical. The projects consisted of several self-guided tutorials and assignments to be completed over the first 4-6 weeks of the course. The stream project, with well structured learning objectives and well defined gradable components, was a vast improvement over the tutorials. The stream project assignments familiarized the students with the design tools they would use for their projects and also introduced many feature concepts of the bus architecture through examples.

In parallel to the introduction of the stream project, the course spun off a second semester component. Previously, students had been able to retake the special topics course again. However, under the new framework two course sections were devised, one for new students – dubbed the "Green Team" – and a section for students looking to continue their work on nanosatellites – dubbed the "Project Team". Students in the second semester were able to forgo the stream project with the expectation that they would make more substantial progress on their project work. Ultimately, being able to dedicate time at the beginning of the semester to train students in satellite design tools while simultaneously allowing students to take an advanced, project focused version of the course once they had acquired the requisite skills, greatly increased the rate of progress generated by the class.

During the period following the expansion to two course sections, the project began working towards its first two missions post-ION: CubeSail, a two-1.5U satellite pair solar sailing demonstration, and LAICE, a 6U atmospheric-ionospheric coupling experiment being built in partnership with Virginia Tech. Due to the designs furnished by the course, all three satellites (the two 1.5U's, and the 6U) share the vast majority of their subsystems components and designs.

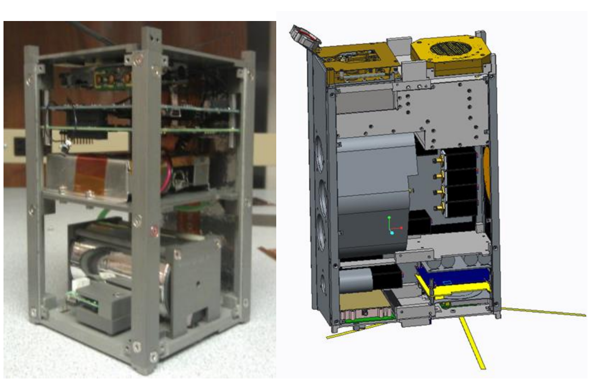

Figure 4: Partially assembled CubeSail 1.5U satellite (left) and the LAICE 6U satellite (right)

Despite the improved rate of progress, our focus as instructors turned to making the course better. The stream project, for all of its instructional benefit, lacked a well structured set of deadlines. Invariably, there existed two types of students: ones who would diligently progress on the stream project throughout the 4-6 week period, and those who would wait to the final week. The stream project was quite time consuming – a necessity based on the volume of content and experience it attempts to instill. Ultimately, those who would wait to the last week would perform poorly thus sacrifice a large portion of their grade. Furthermore, they would tend to adopt similar attitudes toward the course project. Those students were unprepared for the consistent and rapid pace of progress required for the project portion of the course following the stream project. As a result, that stream project period of the course – which lasted 4 years – was marked by atypically bi-modal grade distributions with a long tail (Figure 5).

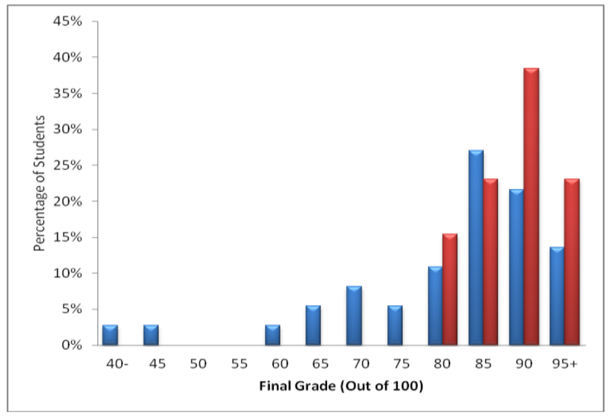

Figure 5: Distribution of grades during the first 3 years of the stream project (blue) and the first semester post-stream project (red).

The stream project also required substantial commitment from the instructional staff in terms of office hours and emails to assist students with questions pertaining to the stream project. The single deadline submission also meant students would progress through the projects at varying speeds forcing the instructional staff to jump back and forth between topics when assisting students.

Seeing the advantages of the stream project, we strove to implement the same kind of learning objective based curriculum in a more structured format. This was achieved by condensing both stream projects (aerospace and electrical) into a series of tutorials, labs, and homework assignments. The tutorial series will be described in more detail when discussing the current implementation of the course below. This new framework maintained the training structure implemented by the stream project, while reducing the burden on the instructional staff, and better acclimating students to the project work environment. While the sample size remains small, the median grade increased substantially following the change despite maintaining many of the same gradable components from the stream project. Perhaps more importantly, retention of students from the first to the second semester also improved, going from an average of 17% retention to 45%.

CURRENT COURSE FRAMEWORK

As stated, the course is in fact a series of two courses meant to be taken in successive semesters: an introductory semester which familiarizes students with the satellite framework and design/analysis tools; and a project semester in which students work to progress satellite hardware. Rather than being independent and distinct, the two courses share a common lecture room, lecture time, instructional staff, and lab space; they do, however, have completely distinct learning objectives.

Introductory Semester: Green Team

At the start of their first semester, even the highest achieving students are ill-equipped to make substantial progress on satellite bus subsystems. In order to prepare the students for making substantial progress on satellite hardware projects, we expose them to the tools they will be using through a 4 week long series of tutorials, labs, and homework assignments.

After an introductory lecture in which we familiarize the students with the course structure and learning objectives, we move the following lecture period to a computer lab for the next 4 weeks to begin the tutorial sequences. Students are first exposed to mechanical CAD software (ProE in our case). The CAD sequence begins with a guided tutorial which is detailed for the students in a document located on the course website. During the tutorial, an instructor steps through the tutorial while students follow along on their own machines. A second instructor typically moves about the computer lab assisting students who encounter difficulty. The pace of the tutorial is fast – the expectation is that the student will refer back to the tutorial material when completing the lab and homework. The tutorial covers very basic operation of the software (creating parts, navigating, performing simple analysis) while familiarizing students with the capabilities of the tools.

In the lecture period immediately following the tutorial, we hold the lab exercise. In principle, the tutorial and lab are identical: the students follow a prescribed set of instructions using the software on their own machines while the instructor demonstrates on a projector. The two differ in that the lab demonstrates more directly how the software can be applied to the satellite hardware. In the case of the CAD sequence, students modify parts of the existing satellite while being exposed to more advanced features. This serves a dual role of expanding the students' abilities with the software, while concurrently introducing them to the satellite bus architecture. Similar to the tutorials, the pace is fast and is meant to expose students to the capabilities of the tools rather than to build true proficiency with the software. The lab concludes with the students taking a "ready-to-manufacture" step. In the case of the CAD sequence, students create a stereolithography file of a sensor housing they modeled as part of the lab. A premade 3D version of the housing is then presented to the students as a demonstration of the work they completed.

In addition to expanding the students' exposure to the tools, the lab session serves as a direct introduction to the homework. By design, the first homework problem is a direct extension of an element of the lab. Subsequent problems challenge the students to apply the skills they learned in the tutorials and labs to create simplified versions of satellite components. The homework problems also serve as additional instructional elements introducing students to new features of the software. The homework sets are not altogether difficult, but they are time consuming. This is explicitly stated as being a way to get students accustomed to the work they will be doing on the satellite projects which follow the tutorial sequences.

Following the CAD sequence, we restart the process with a sequence on orbital mechanics/attitude control using AGI Satellite Tool Kit and MATLAB. This is followed by a sequence on sensors using LABVIEW, and the series is completed by a sequence on electronic fabrication using EAGLE.

While the tutorial sequence familiarizes students with design and analysis software and also providing gradable components in the form of homework assignments, its true value lies in the empowerment of the students. Each lab's "ready-to-manufacture" component builds on the previous sequence to create a functional satellite component. The orbital mechanic sequence has them code a rudimentary attitude determination algorithm, which they then interface with a premade sensor they use in the sensor's lab, which is then replaced by the magnetometer circuit they layout in the electronic fabrication lab, which in turn mounts to the housing they created in their CAD lab. In truth, the students have not manufactured any of these components – these components were pre-fabricated as demonstrations of what could be created from their "ready-to-manufacture" step. To the student, the sequence demonstrates to them that they now possess the requisite knowledge to create satellite components.

The empowerment from the tutorial sequence overcomes the problem of "analysis paralysis". In earlier incarnations of the course, we discovered that many students would spend substantial time researching their projects and delaying designing and testing. The extra time researching seldom provided the knowledge that learning from a failed design would garner. It also delayed progress and decreased the final quality of the designs. After implementing the tutorial sequence, students were more prone to move to the design phase and the quality (and volume) of the progress made increased substantially.

During the fourth week of the course, the students are instructed to review the list of available semester project summaries. The project summaries are descriptions of the various subsystems that need to be advanced during the semester. The descriptions include some contextual information about the topic subsystem, the list of objectives we expect to be completed by the end of the semester, and a brief list of the subsystem requirements (Figure 6). The project description also identify how many and what type of skills sets are required for each project by way of identifying specialist roles – e.g. Electronic Layout Specialist, Programming Specialist, Mechanical CAD Specialist, etc. These roles help students identify and assemble from among the interdisciplinary group a team that will be able to accomplish the project objectives.

After the conclusion of the tutorial sequence at the end of the fifth week of instruction, students are assigned to their subsystem teams. Back in the lecture setting, each team engages in a proposal workshop in which they must outline a semester proposal based on their project summary. During the workshop, the instructors guide the students in developing a formal list of subsystem requirements, furnishing a list of objectives and milestones, detailing each objective, and creating a timeline and budget. The workshop lays the foundation for the proposal; each group is responsible for editing and submitting a formal proposal as a graded assignment. Once the proposal is accepted, the group begins their work on their semester project.

Following the tutorial sequence and subsequent proposal workshop, students begin work on their projects. By this point, they have already been exposed to the lab spaces through introductory tours and have been introduced to the satellite design through the tutorial sequences. Outside of class time, students are expected to make progress on their designs. They are encouraged to meet weekly with an assigned instructor who specializes in their subsystem to ensure the designs stay on track. Throughout their projects, students are required to fill out a log book with all of their findings, results, and design concepts. This assists in their

S14.4 Ground Station Operational Readiness

Team Specifications: 3-4 Members (3-4 Ground Operations Specialists)

The CubeSat group at the University of Illinois possess a sophisticated ground station including an antenna mounted on the roof of Everitt Lab, and a small ground station located two floors below. This ground station has been used in the past to track satellites but has not been used within the past 5 years. During that period, a new azimuthal motor was installed, though never test. Prior to the completion of the semester the antenna and ground station need to be brought online and used to track satellites already up in space, while also updating the existing hardware and software to improve performance and automation.

Expectations for the Semester

The team is expected to finish the following during the course of the semester:

1. Erect the existing antenna on Everitt Lab and test that the motors are functioning properly.
2. Bring online the existing ground station software and ensure that the ground station can track a satellite trajectory.
3. Use the hardware to capture satellite beacons.
4. Research improved software to allow for the satellite to be 1) operated remotely and 2) operate autonomously, and implementation changes to the system.
5. Create a secure intranet link to the ground station so that it can be operated from the primary lab facilities.
6. The Ground Station Operations documentation must be updated.

* Note: At least one member of the group (preferably all) will have to receive certification as an amateur radio operator during the course of the semester.

Figure 6: Example of a project summary provided to the students.

meetings with instructors and each other while it also serves as a reference for their final documentation.

While working on their projects outside of lecture, the lectures take the form of special topics lectures and weekly systems meetings which continue for the majority of the semester. During the first lecture of each week, an hour long special topics lecture is presentation by one of the instructors or guest lecturer on a topic relevant to nanosatellite design. In earlier versions of the course, we attempted to provide survey level lectures on core topics such as orbital mechanics, space environment, electronic fabrication, satellite communications, etc in lieu of special topics lectures. Unfortunately, as the content was covered in more detail in other courses offered in the electrical or aerospace engineering department, it was often a rehashing of concepts for the half of the students who had taken those courses while simultaneously being too obtuse for the rest of students to appreciate or find useful. Instead, we opted to focus the special topics lectures on emerging topics in the field of nanosatellite research, often drawing from current events to demonstrate the relevancy of the research the students are performing. The content has ranged from nuclear powered cubesats, to new mission concepts, to the emergence of new standards for the 6U bus form factor. The content of the lectures is not evaluated on any tests or homework; however, attendance is enforced through a weekly log book check. The log book is checked, stamped, and signed by an instructor and returned to the students prior to the end of the special topics lecture.

During the second lecture of each week, a systems meeting is held. During the meeting, each group must present the progress made on their project to the course staff and other student groups. Each student is required to report on their individual project progress in a brief progress statement. The students are encouraged by the course staff to practice delivering their findings in a concise manner as one would expect in an industry setting. This is also an opportunity for students to ask of the course staff and of each other any system level issues that come up. Often, different subsystem groups need to work out interface issues and this forum is a perfect venue for that. In many cases, mission PI's working with the CubeSat group (who are typically distinct from the course staff) attend the meetings when it is pertinent to help inform students on design intention and requirements. The systems meetings also help keep students accountable to themselves and each other – having to report on progress weekly ensures consistent progress is made.

Toward the end of the semester, the students are graded on a demonstration of their project. The demonstration is to be done in a lab setting and demonstrate the progress made during the semester. Depending on the project, this demonstration may be functional test of a prototype circuit, a demonstration of a new qualification test procedure, or a unit test for a new code base. The demonstration is supposed to represent substantial progress though not necessarily a final product for the semester. The demonstration offers the entire staff an opportunity to offer recommendations for the final design.

During the final week of instruction, the students are required to give a final presentation on their project subsystem. The presentation is in the form of a short (15-20 minute) talk with accompanying slides to the class and a panel of outside reviewers. The panel typically consists of mission PI's, faculty not associated with the course, and local industry professionals. The presentation is followed by a question period and students are graded on the quality of the content and delivery.

The final graded component is the final documentation. Unlike many senior design level courses where the final documentation takes the form of a summary report, the students are required to update and create system documentation. In many cases, students will be updating existing documentation and submitting revisions rather than creating entirely new documentation. This is meant to maintain continuity of projects across semesters, and ensure that documentation about each subsystem remains complete and relevant. The documentation is the single largest gradable component and the importance of the documentation is regularly emphasized to the students. A special topics lecture is dedicated to technical writing each semester to further reinforce the importance of proper documentation.

By the conclusion of the first semester, the students have designed and tested prototypes which fulfill most of the requirements for flight. Due to time limitations, their projects still lack the maturity required for integration into the satellite bus. By virtue of the fact that much of the research is exploratory in nature, some designs ultimately fail to achieve the requirements and will be redesigned in future semesters. That said, most will continue to be evolved by the project team in subsequent semesters.

Project Semester: Project Team

After completing a semester on the green team, students may progress to the second semester course. The project semester is a distinct course in the university course catalogue from the introductory nanosatellite design course describe above. Having taken the introductory course, the students come into the project team with mastery of the tools, understanding of the satellite architecture, and capable of leading subsystem design work. Most frequently, students in the second semester elect to continue the work they started in the first semester and evolve the design to a flight ready status.

During the first week of the course, the students will complete a proposal workshop, very similar to the workshop they completed in the first semester. The scope of the objectives tends to reflect the expanded timeline of the second semester and the student's superior familiarity with the project topic in comparison to the first semester's proposed objectives. The proposal is graded and the student begins their project.

In the third week of the course, the students present their proposed finals designs to the course staff in a 30 minute design review. The design review is meant to scrutinize the system to ensure that it complies with all satellite interfaces, standards, and system/subsystem requirements. The staff typically provides the student a series of recommendations for their design as well as assessing a grade for the presentation.

In the fifth week of the course, the students perform an early semester demonstration. This is similar to the demonstration at the end of the previous semester, and is meant to show how changes from the design review have been implemented (Figure 7). By this stage, prototypes have been fully designed and tested and flight designs are ready to be manufactured and tested. This demonstration is also graded.

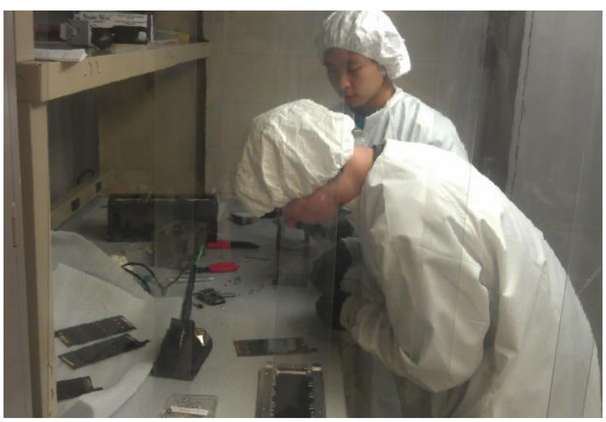

Figure 7: Project semester students performing a demonstration in clean room of their functional protoflight solar panels.

Following the early semester demonstrations, the project team joins the green team for the special topics lectures and weekly systems meetings. As the special topics courses change from semester to semester, they will be exposed to new content. During the initial systems meeting, the project team encourages the green team to make quick progress on their project. Very much by design, the project team is five weeks into their projects (which again are typically continuations of the projects they completed the semester prior) while the students in the introductory course are just beginning their project work. The disparity in the progress being reported has a decidedly positive impact on the green team project progress in subsequent weeks.

For the remainder of the semester, the project team's timeline runs parallel to the first semester course. The project team is required to maintain their log books (their original log books having been returned at the start of the second semester). They participate in the demonstrations now demonstrating fully functional flight components. Similarly, they conclude their semester with the presentation and submission of their final engineering documentation. The rubric emphasizes final demonstration and final documentation in lieu of the homework sets from the first semester.

It is important to emphasize that it is during this course that most of the productive work on the satellite bus is done in the class setting. Despite the green team typically out numbering the project team 4-to-1, the students in the project team are more readily able to make substantial contributions to the satellite. At this point in the IlliniSat-2 bus development, it is too difficult for students to gain the requisite skills and advance a design to flight readiness in one semester. In contrast to the introductory course, the project course also requires significantly less involved instruction. This lesson was extremely valuable for focusing on developing the satellite bus – improving the enrollment in the second semester course was ultimately the most effective way of improving the rate of development on our missions both in terms of progress, and time investment on the part of the instructional staff.

APPLYING LESSONS LEARNED TO NEW COURSES

The nanosatellite design course at the University of Illinois has been an invaluable tool for educating young engineers. Graduates of our course have gone on to successful careers in satellite research and development at every major space technology firm. The program, after 15 years remains a large draw for incoming students, while providing a unique capstone experience for electrical engineering and aerospace engineering majors. We recognized that this program allowed us to teach the same systems engineering design concepts in a very engaging and compelling way that could be expanded to other topics than systems engineering. We will briefly summarize a course on mission operations we are in the process of developing to compliment the course.

Mission Operations Course

The new course will introduce space mission operation concepts through a series of lectures accompanied by a strong lab component to apply those concepts to simulated mission scenarios. The course labs will be operated within a currently proposed ground operation center at the University of Illinois (see in Figure 8). The ground operation center will already possess most of the requisite software and hardware for performing mission operation simulations (as well as perform real mission operations for our nanosatellites when not used for the labs).

Figure 8: Proposed ground operation center at the University of Illinois

The course framework will borrow lessons learned from the nanosatellite design course. The mission operations course will implement a series of guided tutorials which directly apply concepts learned in the classroom. The latter half of the course will include a small design project in which students will have to propose actual mission concepts which will be tested in simulation in the lab. The students will then evolve a set of documentation that improve the overall mission operations of the existing nanosatellite projects following a review process and final presentation.

CONCLUSION: LESSON LEARNED

The nanosatellite design course has, through its ever evolving manifestations, provided a wealth of lessons for us as instructors. We have attempted to distill these lessons down to a core set which we believe provide the best framework for similar courses.

1. Even at its best, the course is not a reliable method for advancing a nanosatellite design. The course can make substantial progress during a semester, but it is difficult to guarantee progress through the course.

2. Long term project thinking is a must. Formal documentation chains, typical of much larger projects, are necessary to help the project span decades of work.

3. Recruiting and retention are paramount for success. Sophisticated nanosatellite designs require students with significant training seldom offered to students through the standard curriculum. Training a large number of students and ensuring they have an experience that encourages them to return is critical in building a corps of students who can make substantial progress.

4. Education must remain the mission of the course. While it is easy to become focused on launch dates and mission timelines, the course must remain focused on building engineers and not satellites. The nanosatellite is the vehicle to inspire students to learn, but from the perspective of the course it cannot be the goal.

ACKNOWLEDGMENTS

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