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The University Nanosat Program from Concept to Flight: A Dual Student Program Perspective on What Works and What Does Not

Scott Franke Air Force Research Laboratory, Space Vehicles Directorate 3550 Aberdeen Ave SE, Kirtland AFB, NM

Marcin Pilinski, Millan Diaz-Aguado Department of Aerospace Engineering & Engineering Mechanics University of Texas at Austin 210 East 24th Street, W. R. Woolrich Laboratories 1 University Station, C0600, Austin, Texas 78712-0235; 512-471-7593 lenartmd@mail.utexas.edu, mfdiazaguado@mail.utexas.edu

Stephen Forbes Department of Mechanical & Aerospace Engineering Washington University in St. Louis Campus Box 1185, St. Louis, MO 63130-4899; 314-935-6047 <u>sef1@cec.wustl.edu</u>

George Hunyadi Jackson and Tull Chartered Engineers 1601 Randolph Rd. SE, Suite 100N, Albuquerque, NM 87106 <u>ghunyadi@jntsw.com</u>

ABSTRACT: The University Nanosatellite Program of the Air Force Research Laboratory provides a paradigm-changing environment for the leaders of tomorrow's space industry to envision solutions for today's small satellites. The products of the Program are an educated, experienced workforce that will meet the demands of tomorrow, along with a spectrum of small satellite technologies onboard student-built nanosatellite flight missions. This paper reveals intangible aspects of the systems engineering and integration process that are usually lacking in new hires. Students involved in the UNP program come out with an experienced perspective well beyond what the current higher education system provides. Examples of success and failure at the university level are presented. Management of technical and programmatic requirements and risks are addressed, including such issues as constricted university budgets and heavy personnel turnover. Quality control and systems engineering methodologies are also discussed. Two separate, concurrent University Nanosatellite Program-sponsored projects will be presented as case studies.

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INTRODUCTION AND BACKGROUND

The University Nanosatellite Program (UNP) of the Air Force Research Laboratory's (AFRL) Air Force Office of Scientific Research (AFOSR) and Space Vehicles Directorate (VS) provides a paradigm-changing environment for the leaders of tomorrow's space industry to envision solutions for today's small satellites.

The University Nanosatellite Program is a one-of-a kind outreach operation which develops partnerships between the Air Force, NASA, AIAA and industry participants and universities interested in small satellite design and flight build. This symbiotic relationship allows for a direct link between experts in the field and students working on small satellite projects at the university level. The result of that interplay is a unique educational experience based on rigorous engineering practices.

Created in 1999, UNP has evolved into a two-year recurring university student satellite competition. Through funding, workshops, and an intense projectreview process, the program allows students to gain a wealth of experience while implementing their ideas in flight-worthy space-hardware. In return, the university students provide development of technologies of interest to the small-satellite community, and discover low-cost solutions to existing problems in the field. Approximately a dozen U. S. universities participate in each two year competition. The universities all develop their own individual missions and hardware. At the end of the two years, the winner of the competition is chosen to go through final integration and test at AFRL. The products of the Program are an educated. experienced workforce that will meet the demands of tomorrow, along with a spectrum of flight-worthy technologies, and flyable nanosatellite missions.

LEARNING EVOLUTION

In today's environment, the spacecraft industry's products are specifically designed for a certain mission. Even experimental satellites cost an estimated \$50-100 million to go from concept to flight. Operational systems have per-unit costs of hundreds of millions to billions of dollars. An analogy to a car manufacturer being required to design a car to one individual's preferences can be drawn. Imagine if Ford Motor Company had to build a car not only for example, "middle class single men, 25-35", but for "John Smith, 5' 7", 156lbs, lives in Colorado where there is a 47.6% chance that he'll need to drive up curvy mountainous roads in the wintertime, has 2 dogs that shed, has back pain, large fingers, plays soccer twice a week, and if he

drives a Dodge, Ford goes out of business." The specifications in the space industry run parallel to the latter type of detail. More often than not, designers must learn how to fit the puzzle pieces together in a tug of war between disciplines in order to walk the thin line between achievement and ineptitude.

How does one change this model? Can it be changed? Should it? Here, we only provide an account of how U.S. universities within the University Nanosatellite Program have started, in essence, an experiment in evolution driven by the extreme environment of short duration, personnel turnover, inexperience and little corporate memory, and evaporative budget limitations. In essence, the Program is Darwinian-subjecting its participants to survival within an intense, real-world environment, forcing the students to quickly learn the design, build, and test techniques which work the best. Time and schedule shape the design-to-build environment in which the university programs compete to meet the UNP criteria, the requirements imposed by their missions, and to build functioning flight-hardware. The university with the leanest solutions has the "best" space mission and hardware, and wins the flight competition. Through this process, an exceptionally talented and experienced new workforce evolves.

The university team participants in UNP are severely constrained: build a spacecraft in less than two years from scratch with a few dozen untrained students, no real world experience, balance the rigor of an engineering or science curriculum, and, by the way, the spacecraft mission needs to be state of the art. Do this for free (or much less per year than you will make as a starting engineer), all the while maintaining your grade point average, and possibly writing a thesis.

Of course, while the environment of resource constraints is extreme, the Program Office at AFRL provides substantial guidance. Program requirements and constraints are delineated and design standards and suggestions are "highly encouraged" to all universities in the competition. By having the general problem (designing a mission from scratch) bounded for them, the schools' efforts usually progress to similar nanosat bus systems, while maintaining very unique payloads and mission architectures.

The glue that holds everything together is the long term memory of AFRL personnel and a robust systems engineering process. Dedicated systems engineering processes account for professional quality of the student-built designs, without wasting university (and government) time, money, or personnel resources. To accomplish this, considerable effort by students and AFRL personnel is required. Industry-standard best practices, such as developing rigorous mission-driven requirements up front, adherence to specific documentation standards (prove on paper what you build), and the philosophy of simplicity and safety of design are constantly hammered into the students' mindsets. The highest achievers in the competition employ strict systems engineering rigor to their design process. The more experienced students typically gravitate to the student systems engineer role in their respective university design teams. The effort required to build a flyable nanosat is exhaustive. During critical design, build, and test periods, Nanosat team members typically sleep a handful of hours per night, forego lucrative internships, and sacrifice social life with no motivation other than the slim chance that what they work on will indeed someday orbit the earth. Upon graduation, their experience often lands them in aerospace positions with salaries years beyond what the typical "fresh-outs" earn.

WHY ARE WE DOING THIS?

"Now is the time to reignite the passionate interest in space and science education. However, the manner that we go about doing this is critical to success. We cannot be content with short-term solutions for ideas or thinking." – Dr. Patricia Arnold, Vice President of Education, U.S. Space Foundation

The prime driver for UNP is the education of America's space workforce in the 21^{st} century. As Figure 1 illustrates, the size of the U.S. aerospace workforce has steadily declined since the 1980's, and needs replenishment if the U.S. is to maintain a leadership role in space.



"The need to replace retiring workers over the next 10 years, however, demonstrates the crucial need to start refilling the "pipeline" of qualified workers now. Analysis of the economic benefits of apprenticeship programs shows an impressive \$50 return for every dollar of federal investment." – Final Report Of The Commission On The Future Of The United States Aerospace Industry, Nov 2002.

The University Nanosat Program survives on funding literally orders of magnitude below the average spaceflight program in the U.S. This is not to compare the quality of flight products, but only to make the point that education efforts within government and industry need not take on gargantuan investments to achieve the maximum desired effect, which is giving trainees extensive real-world experience. This effects-based education method fills the critical space systems engineering gap in U.S. university curricula, at minimal cost to the taxpayer, while greatly benefiting the space industry.

Figure 2 illustrates the decline of enrollment of aerospace engineering undergraduates in American universities for the years shown. While there is a slight resurgence, many of the enrollments are foreign nationals, contributing little to the long term replenishment of the U. S. workforce.



Figure 2. U. S. University Aerospace Engineering Enrollments, 1987-2001 ³

Since its inception, thousands of science and engineering students have participated in UNP, from freshman up to PhD candidates. UNP involvement since the Program's inception in 1999 has been 30 U.S. universities, with approximately a dozen being funded during any given two-year Program cycle. UNP also maintains contacts with approximately 15 U.S. universities that have healthy space curricula. The Program has been credited with assisting burgeoning university programs—universities that desire a foothold in hands-on space research. It is likely that the upward trend shown in aerospace enrollments may be at least partially attributable to programs like UNP. For the participating students, what is discovered is that attitudes of the team—especially the acceptance of real engineering responsibility on the part of the individual members-is inherently critical. This "real-world" lesson is highly valuable, as individuals can see immediately the effects of their efforts. At the university level, without the burden and empowerment falling directly on individuals (coupled with the false assumption that someone else will pick up the burden once dropped), the education value is greatly diminished and the hardware design and build efforts are unsuccessful. Regardless of each team's level of success at integrating a working, flyable spacecraft, the University Nanosat Program always achieves its goal of a highly talented, experienced workforce. Those universities that do succeed to flight gain exposure to the full space mission lifecycle before they even enter the workforce—an accomplishment that many professional U.S. aerospace workers never experience over the course of their entire careers.

TECHNICAL AND PROGRAMMATIC RISKS

Just as the universities operate under severe constraints (programmatically and technically), those responsible for sponsoring and running educational, high-risk flight programs such as UNP are faced with similar challenges. The difficulty of UNP is in the balance between achieving a worthwhile and high yield educational program, while still holding to tight schedule and funding constraints. The UNP Program Office at AFRL faces the challenge of "bringing students up the learning curve" during the flight competition phase. Occasionally, momentum fluctuates from one design review or event to the next based on the commitment to excellence that the students have invested at that section of the competition, but in general this phase runs more or less smoothly, due to the fact that most of the participating students are highly motivated.

The real challenge exists at the end of the flight competition, after the downselect to the "flight" nanosats, where there exists great tension between educating students in assembly, integration, test, launch, and on-orbit operations, and finalizing a real, flyable satellite product. Without a potential flight, the intrinsic student motivation is greatly reduced. The constraints of personnel turnover, very small budget, and short schedule still exist at the university level, with the added burden of yet-more-unyielding government schedule and budget demands. For the flight competition winners, Program tolerance for "amateur" mistakes is greatly reduced if the satellites are to make The real insight is how much the it to orbit. government at this point should control the decisions

and activities of the learners? On one hand, students should be held to high responsibility over their designs and hardware, but on the other hand, lack of experience causes a certain amount of unpredictability at the potential expense of delivery and flight. At what point does the significant effort required to fly start to supplant self-motivated student education? The answer lies in the fact that most of the effort of flying a satellite occurs after the design phase, during assembly, integration, test, launch and on-orbit operations. Therefore, the UNP Program Office gives significant management and systems engineering assistance to the winning universities during these stages-including help with designing simple, robust GSE, launch vehicle, and ground operations interfaces-in an effort to expose the students to the intense nature of these processes. This delicate "hands-on-vs-hands-off" balance enables the students to experience and run a real flight program, while knocking down the substantial roadblocks to flight for "amateur" payloads. In the end, this approach allows UNP to maintain both the flight aspect and the educational excellence of the Program.

While all of the teams participating in the flight competition learn the rigor of design, communication and commitment, the truly unique experience occurs for the satellite designs that are chosen to continue on to integration and test. The university is still the expert on the satellite and integration can not proceed without the university. Here, the students not only learn to support the operations of their satellite but experience what many do not get to experience-the substantial technical, managerial, economic, political and personal effort required to place a spacecraft on orbit. Certain universities have approached this in several different ways. First, some have fielded a veritable army of students and can easily support activities either remotely or on location at test facilities or launch-the students not necessarily having to be overly dedicated individually. Second, some universities can support such activities equally well, but supplement students with full-time university employees who understand the satellite system and provide a corporate memory in the face of student turnover. Third, some universities have a very small group of the core student team that are dedicated and motivated enough to expertly know all systems and give up a significant amount of their time to the program. From previous UNP experience, the Three Corner Satellite (Nanosat-2)-built by New Mexico State, Colorado at Boulder, and Arizona State Universities-had all three types of support. Is this necessary? Experience says yes. The critical factor is the ability for the university to provide the necessary support at any given time-the student expert that knows critical details of the design, the corporate

memory (to prevent reinventing the wheel), and the army of personnel that can support critical activities like integration and launch opportunities. Fundamentally, this applies to the UNP Program Office as well. The UNP Program Office at AFRL runs most effectively with one entity providing direction and corporate memory (program manager), one entity having depth of expert knowledge on the systems (systems engineer), and a backup army of engineers and technicians that provide integration, test and launch support. With both the government system and the university system mirroring each other, there is the added benefit of some redundancy and the system works.

UNP PARTICIPANTS' PERSPECTIVES

"It's like being fired out of a cannon at a stampeding herd of buffalo" – Greg Holt, University of Texas PhD candidate, preparing new students for a technical review by the UNP Program Office.



Figure 3. Nanosat-3 Flight Competition Review

The benefits of the UNP are made clear by examining the experiences of its participants. Most students enter the Program with a very theoretical background in engineering and perhaps, some limited research or design experience. All universities provide students with a thorough background in analysis and the theory of engineering in many sub-disciplines. However, the design process largely resides on the periphery of this education and is left to semester-long senior design projects and independent research courses. This is due to the very nature of most institutions of higher education. Independent research in the academic setting usually lacks intensive oversight from practicing spacecraft engineers, while the senior-design classes involve mostly short-term paper-projects with at most a brief foray into the manufacturing process. From the perspective of one student: it is curious to note that while architecture students and other scholars of design spend years of their education in studio courses, honing creative problem solving and implementation skills and complementing their theoretical education with a solid immersion in practice, the average student of

engineering design does not begin this essential transformation until he or she enters the workforce. In marked contrast, by the end of their UNP experience, students participating in the Program have designed, manufactured, properly documented and system tested their protoflight spacecraft.

The University Nanosat Program has the best and brightest students at its fingertips to offer opinions on the satellite design and competition process. Among the eleven schools competing in the Nanosat-4 competition, and the thirteen schools that completed the Nanosat-3 competition, students from two schools were asked to provide a brief synopsis of lessons learned and a record of successful implementations, challenges to overcome, and the critical all-important intangibles.

Washington University in St. Louis is a participant in the Nanosat-4 competition and was a top finisher in Nanosat-3. Their nanosat system, "Bandit/Akoya", faces challenges both common and unique. Bandit/Akoya is designed as a drone/mother spacecraft, in which Bandit deploys from Akoya and performs proximity operations, docking and recharge with Akoya.

The University of Texas at Austin was chosen as the winner of Nanosat-3. Their FASTRAC (Formation Autonomous Spacecraft with Thruster, Relativenavigation, Attitude and Crosslink) satellite design landed them the job of taking their engineering design unit concept to a flight quality spacecraft in a year's timeframe, along with the associated additional challenges faced by this rigorous process. The two identical FASTRAC satellites are designed to separate in orbit and perform relative GPS navigation using single-antenna attitude determination. FASTRAC is the first student built satellite project at The University of Texas.

Student Leadership Challenges and Rewards

"We are doing something no one has done before." – Dr. E. Glenn Lightsey, UT-Austin Professor of Aerospace Engineering and Principal Investigator on the FASTRAC project

The Bandit/Akoya project has had a "collective" of student team managers, in which the students with the most education experience and involved the longest are by default part of project management. In the case of FASTRAC, the project has had two student leads since the beginning of the Nanosat-3 design competition (2003). The first lead, now a graduating PhD in aerospace engineering, led an initial group of about 30 UT students on FASTRAC, while teaching

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undergraduate classes, and a working on his dissertation. The subsequent student leader literally "grew up" from within the project, starting out as undergraduate on the team, becoming the FASTRAC systems engineer and now the program manager, while completing a Masters degree in aerospace engineering.

Successful communication between team leaders and the UNP Program Office at AFRL, and between team leaders and the team workers is the key to success for any university project involved in the Nanosat Program. On the Bandit project most communication was initially done via email through the student systems engineering lead. Since the role of systems engineering (and hence, the systems engineer) is somewhat of a mystery to virtually all students, this became a problem when the subsystem designs got to the point that they required input from other systems. Communication problems are also made worse by the university environment where project members' schedules and commitment vary widely. Within the Bandit program, a weekly team leader meeting was used to keep everyone abreast of the latest developments. The weekly meetings were most effective when each sub-team presented the previous week's work and outlined the coming week's goals. The Bandit project also used an internal Wiki web site as a central repository to store and share information.

Project scheduling is another area where student leadership encounters difficulty. Many of the problems that arise with schedule are the result of simple inexperience on the part of the student leadership. Without experience with such things as modeling, drafting, manufacturing lead-times, and testing, it is very difficult to estimate how long a task will take, what a reasonable deadline for the task is, and how to break a task into smaller and more manageable sections. This is especially true since most students estimate that the system design and specification process will take up most of the schedule, when in fact the manufacture and test phases are typically the longest in duration.

All universities involved in the Program are encouraged to team with industry and potentially develop mentorship relations. Internships with industry indirectly related to Nanosat are common, which greatly assist in the "training up" of good student project managers. In the past, working level relationships have been fostered and student leaders from the Nanosat teams have been hired into the Program's industry partners upon graduating.

Student Workforce Challenges and Rewards

"A considerable amount of the talent [foreign students on temporary visas] being trained at our universities cannot contribute to the U.S. aerospace industry or to the long-term development of the U.S. economy." – Final Report Of The Commission On The Future Of The United States Aerospace Industry, Nov 2002.

Like other UNP university participants, UT had a small, nuclear design team, a body of students interested in satellite design and flight-build, and the support of talented faculty serving as the investigators for the project. Second only to configuration management, team management is an often-underestimated component of student projects. It is here, however, where the small group-project style setting gives universities an advantage over larger entities. This was particularly critical in the design stage of the UT projects where a small design group of five to ten people was able to implement necessary changes swiftly without the need of complex documentation or extra personnel. This team setting also provided for an efficient means of formal and informal communication between the subsystem-leads and encouraged overlap of responsibilities which eventually fostered a workable understanding of the system-level design. In addition, students beginning in the project had virtually no previous experience in satellite design. Although much had to be learned with the help of the UNP Program Office at AFRL and industry experts, this tabula-rosa effect provided the opportunity for novel approaches to the design and build process. Not being negatively affected by a industry biases, the team was open to any new process or solution which solved the problem within the given constraints.

Student recruitment can be the biggest challenge to a Nanosat team, which is longer term than the typical single semester design project. How does one convince students that they should devote large amounts of their time working on a satellite, instead of some other activity which requires a lower level of commitment? It can be difficult to recruit skilled upper classmen because by the time students reach junior and senior year they have already made commitments to other projects and groups. This was the Bandit team's largest problem. Because of the difficulty of recruiting upperclassmen, that team's approach has been to recruit underclassmen to the program and then train them and keep them involved in progressively larger aspects of the project. This approach worked well, but was a huge time and energy burden to those managing the recruitment effort. The one way in which the Bandit project recruited upper classmen was through independent studies, where the participating students

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worked on discrete aspects of the satellite and received credit for their work.

Turnover is problematic for all UNP participants. On the FASTRAC project, of the seven or so students on the original design team, many graduated, and only three remained during the flight build when the team had grown to roughly thirty people. Larger teams mean higher turnover and loss of knowledge, and as the team grew it became apparent that the configuration and document management methods were insufficient to propagate information to newer student team members, much less to subsequent flight projects at UT (UT participates in both Nanosat-3 and Nanosat-4).

Every May (at the end of spring semester), the most experienced students on the team graduate and leave the team. In addition attrition due to graduation, a certain percentage of students come and go as time, schedule and interest permit. This leads to a very transient work force. The constant turnover magnifies other problems such as inter-team communication and student training. On small teams, turnover can lead to core team members "burning out" over the course of the program as they attempt to "do it all" themselves. The Bandit project experienced this effect during the semester following the completion of the Nanosat-3 flight competition. (Like UT, Washington University participates in both Nanosat-3 and Nanosat-4, and is continuing the Bandit/Akoya development as part of the Nanosat-4 competition.) An entire semester's work was completely lost as the team members, who had been overworked the semester before, recovered and regained their interest in the project. Losses and negative impacts occur as well due to scheduling issues as well. The Bandit team typically loses productivity for 4 out of the 16 weeks in a semester due to exams and breaks.

Since the Bandit project resides in the Mechanical and Aerospace department at Washington University, only mechanical engineering credit may be offered for work on the satellite. As a result, Bandit has a large number of upper classmen mechanical and aerospace engineering students but very few from other majors. The same limitation also applies to lab resources. For Bandit it is difficult to get access to the student electrical and computer science labs, while it is easy to get access to the mechanical labs.

Student Intangibles

After the flight competition downselect, students from the winning design teams are tempted to think, "We won the flight competition! So we're done, right?" Wrong. The real effort is just beginning at this point. The University Nanosat Program, among specifying constraints, requirements, design do's and do not's, technical direction and advice, also offers and requires the students involved to rise to the level of the professional world and produce a rigorous configuration management process. It is said that for a satellite to be successfully launched, that three times its weight in paper must be produced. This is to prove to all stakeholders (including the launch providers) that every possible satellite feature physically built is understood completely; meets all applicable safety requirements; and that all fasteners, software, machined structure, detailing, connectors, surface finish, mass, strength, safety features, and repaired problems are indeed what is physically mated to the launch vehicle. Within UNP, there is an enormous task and challenge to convince a multi-million dollar launch vehicle provider to accept a ~\$100,000 student-built satellite as a secondary payload.

Rigorous documentation and configuration management turned out to be the Achilles heel of many of the universities involved, and even those which had been successful in the past have found themselves unable to pass on information and experience to new students on their teams. It is a common thread that students face stringent documentation most requirements with aversion, and that small student teams (like on FASTRAC) see it as unnecessary overhead. However, as the FASTRAC project progressed and the team grew, many previous mistakes were revisited as a result of information loss. With the help of student management and oversight by the UNP Progrram Office at AFRL, FASTRAC was able to implement a successful documentation subsystem in time to save the flight build effort from coming to a FASTRAC employed a graduate computer halt. science student to build an online document management system. Documents are updated real time and accessed by team members as well as the UNP Program Office to be discussed during system engineering and integration meetings.

An example among the documentation requirements is the structural analysis. Its function is to ensure the satellite is "overbuilt" and will easily survive the launch environment. Due to a lack of a sufficient number of students capable of structural modeling, the finite element models that were produced for the initial FASTRAC concept were never updated as the design evolved. Also, due to lack of design foresight (namely, systems engineering allocation and tracking), the FASTRAC design mass increased substantially during the final stages of design and build. The structural analysis lagged behind this process. Without satisfying the structural requirements (demonstrated in part through analysis), the spacecraft could not be delivered for final integration for flight until this document was produced. The team learned the hard way that documentation is a key schedule driver for any university flight project.

After the Nanosat-3 flight competition, FASTRAC's flight build and hardware acquisition and management process became much more rigorous. The team was under a much more focused level of scrutiny. As anyone in the industry knows, the quality of process oversight is directly dependent on the quality of a project's configuration management, but even a well documented student project still needs to learn the nuances of dealing with and overseeing vendors. The FASTRAC team learned many painful but valuable lessons through missteps in machine shop deliveries, unexpected (unresearched) lead times, and unacceptable certifications of compliance or parts which simply did not meet the specifications. FASTRAC made use of many commercial off-the-shelf (COTS) components for which acceptable documentation is unavailable or nonexistent. The team learned that most vendors are not prepared to deal with the nuances of spaceflight hardware. FASTRAC was able to adapt many of its COTS components for use in space and had to dedicate much project management time to oversee and work extremely closely with vendors and machine shops to the extent required to produce the necessary qualification paperwork.

It is impossible to extol the successes of FASTRAC without crediting the government and industry relationships which were forged during the project, and which serve as a contra-positive to the above paragraph. Notable were the team's interactions with Planetary Systems Corporation, which provided FASTRAC with a flight qualified satellite on-orbit separation system: Composite Technologies Development, which provided state of the art miniature composite fuel tank technology for spaceflight demonstration; and AFRL. which provided the direction to distinguish between critical issues and those which could be easily solved or circumvented. The lesson learned was that the "soft" skills required to maintain personal relationships with other people in the business are key to success. With vendors, FASTRAC was able to obtaining costly and/or process-sensitive components, while providing direct business benefit to those organizations. It was important to seek out the companies willing to put in the extra work in exchange for test data (obtained during FASTRAC system test), student labor, publicity, or potential flight demonstration for their products.

LESSONS LEARNED AND SUMMARY

The single-most important and most-overlooked part of the design process is the establishment of a sound systems engineering process, which begins with rigorous requirements definition and flows down into It is the University Nanosat design synthesis. Program's experience that most universities do not truly understanding the systems engineering process at all. The general lack of space systems engineering training in U.S. higher education "flows up" into government and industry, once students enter the space workforce. Arguably, past failures of government and commercial missions have shown that government and industry still difficulty implementing "good" have systems engineering processes, and would benefit from more and better trained space systems engineers. The primary goal of the University Nanosat Program is to effectively bridge the space systems engineering "personnel training gap" by accomplishing this critical training at the university level (vs. training new hires once they enter the workforce).

UNP succeeds very well at giving students these valuable tools, by giving students involved in UNP the option to initially fail, then learn and eventually succeed, within the context of real-world flight opportunities. The UNP experience produces aerospace professionals who understand the modes, the consequences and the price of failure.

The FASTRAC team ran into many difficulties and slowdowns over the misinterpretation, confusion, and oversight of requirements. While key requirements do flow down from the UNP, many of the team's own objectives were never well-defined in requirement the final documentation before flight build. Furthermore, some requirements which were vaguely defined were not interpreted properly. Having a well defined experiment and flowing down the requirements early on is key to building a successful satellite mission, but maintaining the awareness of those requirements is just as important. Requirements can flow down from mission objectives, launch providers, or the principal investigator, and most students do not realize the importance of requirements sources and documentation to the success of a multi-year flight project. Based on the experience of Nanosat-3, the UNP Program Office has implemented continuous improvement processes which will focus the Nanosat-4 and follow-on competition cycles on the importance and systematic adoption of rigorous systems engineering processes like requirements generation and flow-down, and where they belong in the iterative design process.

For the FASTRAC team, the best systems engineering experience was gained by working with the design and integration of actual flight hardware systems. Starting with the design and construction of the EDU model of the FASTRAC satellite, through integration and test a fully functioning flat-sat (table-top electrical functional model), and putting together comprehensive and updated CAD models, the team was able to learn proper methods of subsystem interface design and test. The team found that most of the technical problems occurred not on the component level, but in the interfaces such as software messages, wiring harnesses, attachment brackets, EGSE and MGSE subsystems, and even the fasteners. This will come as no surprise to experienced engineers but it is important to note that this level of system design awareness comes as a completely foreign concept to most students, who are usually taught to focus on a specific discipline, and in the process "lose the forest for the trees." One of the advantages of a student design-build-and-fly project is that the spacecraft bus engineers and the experiment engineers are able to work very closely and often share responsibilities. Ultimately however, the success of a systems-level design hinges on the team's ability to teach itself the tools and methodology to deal with systems interfaces.

Working in an environment where the students are empowered and have the freedom to experiment with their designs (even to the point of failure) is paramount. The University of Texas Aerospace Department was a great setting for this work FASTRAC effort, and the student Satellite Design Laboratory provided the necessary means for the team to implement their ideas. In a place where problems are solved as they are discovered and where "close-of-business" means bedtime, university students were able to construct novel and industry-relevant technologies on a very short timescale. Also, the determination, talent, and optimism of the student leaders on the FASTRAC and Bandit projects cannot be understated, and is the determining factor in the success of these projects and those like them. Leading by example, the student leaders provide a positive atmosphere for the projects and give the support necessary to overcome the various challenges that arise. In this way, the student projects sponsored by the University Nanosat Program provide a means to learn not only from experts in the field, but for students to learn from the experienced graduate students, essentially building up a new curriculum which teaches the core principles of sound space systems engineering by immersion. Ultimately, the lesson learned (for UNP students and for industry) is that the development, maintenance, and operation of the human element in space missions is by far the most critical key to success.

CONCLUSION

The need for an education experience like that provided by the University Nanosatellite Program is most dire in the area of spacecraft design, where engineers cope with creating technology that functions efficiently, reliably, and remotely in the most hostile of environments. By providing expert oversight, educational workshops, and the sponsorship by which universities can take a small satellite from concept to flight-build, the UNP program trains today's engineering students to be better prepared for the everincreasing challenges of tomorrow's spacecraft missions. Furthermore, the intensity of the program is unmatched in the U.S. by any other design experience on the university level. Students learn not only the principles and practices of systems engineering and satellite design, build, test, and flight, but also learn to infuse the proper rigor and scrutiny into their analysis, design, and implementation. The latter is a key ingredient to all engineering disciplines. Students departing the UNP program for the "real world" find themselves well-prepared to solve industry problems.

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