AC 2007-1409: CHALLENGES FACING THE STUDENT SPACE SYSTEMS FABRICATION LABORATORY AND LESSONS LEARNED

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Abstract

The Student Space Systems Fabrication Laboratory (S3FL) is a student-led organization dedicated to providing students with practical space systems design and fabrication experience not readily available through the usual academic curriculum. S3FL's approach is to enhance space systems engineering education by coupling classroom knowledge with practicum experience involving real engineering design, analysis, test, fabrication, integration, and operation of actual flight vehicles and payloads. Through a continuous learning process and by adapting to new challenges, S3FL has sustained itself despite the difficulties of accommodating an increasing number of student members. S3FL has also been able to maintain effective project leadership and technical expertise despite student turnover as well as to secure external support. The paper discusses the methods and strategies adopted by S3FL to address the challenges facing a student-run lab. Case studies of projects are also used to highlight important lessons learned over the years.

1 What is S3FL?

Since 1998, the Student Space Systems Fabrication Laboratory (S3FL) at the University of Michigan's College of Engineering has combined a formal design process with student creativity and spontaneity to train and provide students with opportunities for research in space systems design and development.[1] Each year, S3FL involves over a hundred undergraduate and graduate students in realistic and intensive design-build-test activities ranging from balloon payloads to microgravity experiments to nanosatellites. By participating in the end-to-end development of complete space systems, students acquire knowledge and expertise that would otherwise take years of post-graduate experience to be achieved.

1.1 S3FL's philosophy

A comprehensive education that prepares students to be strong contributors and leaders in their future careers requires an academic program of both classroom and practical components. Classroom settings provide the foundations of engineering analysis but cannot substitute for practical, hands-on experience gained from real-world problem solving in end-to-end projects. S3FL's objective is to provide students with the opportunity to learn, develop, and practice the engineering, teamwork, management, and leadership skills required as members of the nation's future space workforce.

S3FL offers students the following opportunities[2]:

- Hands-on projects to apply classroom knowledge in real-world, interdisciplinary settings
- Experience working through a complete design-build-test cycle
- Development of a systems engineering mindset

1.2 Lab organization

All day-to-day activities in S3FL are student-run, with administrative support provided by the student Executive Committee (Excom) and faculty advisors. Figure 1 shows the organization of the lab via projects that are directly overseen by Excom members, who are qualified graduate or upper-level undergraduate students with prior project lead experience. These projects range from top-tier, multi-year efforts involving dozens of students on satellites and Space Shuttle payloads[3-8] to smaller, months-long design projects (e.g., BalloonSats,[9] NASA microgravity flights,[10] CanSats,[11] etc.) intended as training programs for newer students and test platforms for prototype design development. S3FL has also diversified its lineup of projects in recent years to participate in various aerospace systems competitions (e.g., NASA's Revolutionary Aerospace Systems Concepts – Academic Linkage,[12] undergraduate competitions from the American Institute of Aeronautics and Astronautics, etc.). In addition, teams of students participate in specialty groups to support S3FL activities.

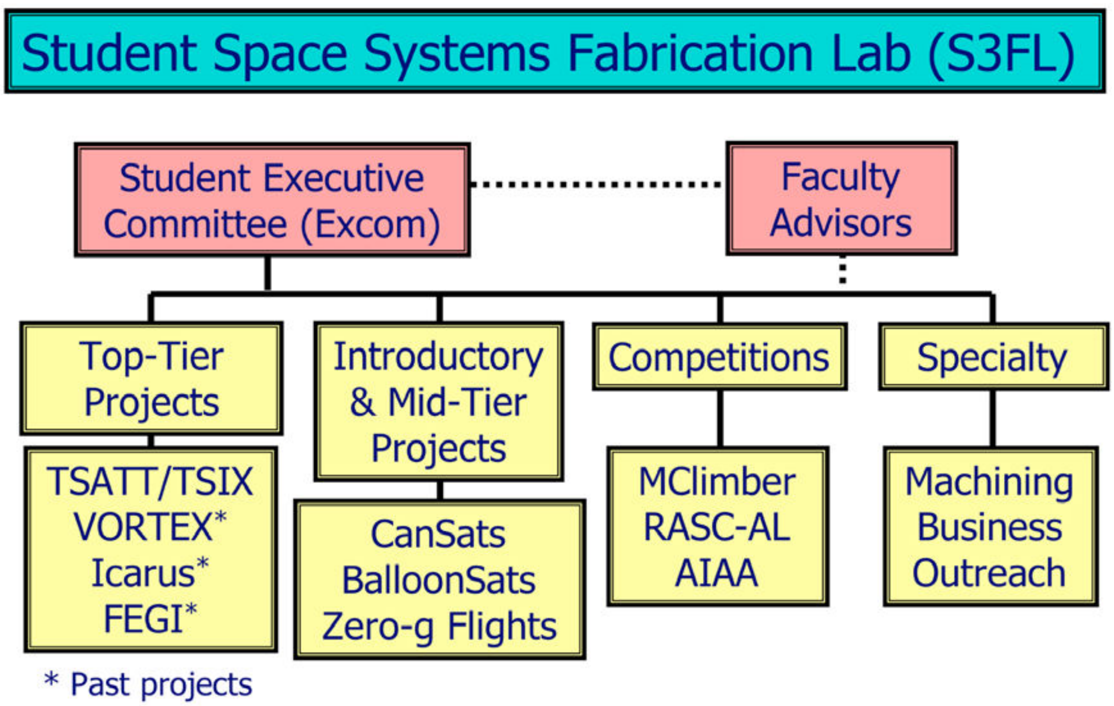

Figure 1: *S3FL's project organization.*

S3FL has over a hundred students currently working on its projects. Depending on interests and capabilities, the students participate via the Undergraduate Research Opportunities Program (UROP), dedicated design or project experience courses, senior-level directed-study, major design experience credit, and work-study as well as volunteering. Table 1 shows the distribution of students for the 2006-2007 academic year. The vast majority of S3FL students come from the Aerospace Engineering (AERO), Electrical and Computer Science Engineering (EECS), and Mechanical Engineering (ME) departments, with about 20% of the students coming from other academic disciplines. A group of graduate students, many from the Master of Engineering in Space Systems program in the Atmospheric, Oceanic, and Space Sciences (AOSS) department, provides critical technical and managerial expertise.

Field of Study	
Aerospace Engineering	51%
Atmospheric, Oceanic, & Space Science	3%
Electrical & Computer Science Engineering	15%
Mechanical Engineering	15%
Other (Physics, Industrial & Operations Engineering, etc.)	16%
Academic Level	
Undergraduate	92%
Graduate	8%
Participation Mode	
Credit (directed-study, design courses, & work-study)	74%
Volunteer	26%

Table 1: *S3FL personnel statistics for 2006-2007 academic year.*

2 Challenges facing S3FL

As a student organization, S3FL has faced and continues to face a number of challenges in remaining self-sustaining while staying true to its founding principles. Over the years, its students and faculty advisors have worked and continue to work to address these challenges.

2.1 Accommodating an increasing lab population

As shown in Figure 2, the number of S3FL members has increased dramatically in recent years, almost tripling from 2003 to 2005 before leveling off as the lab consolidated itself.

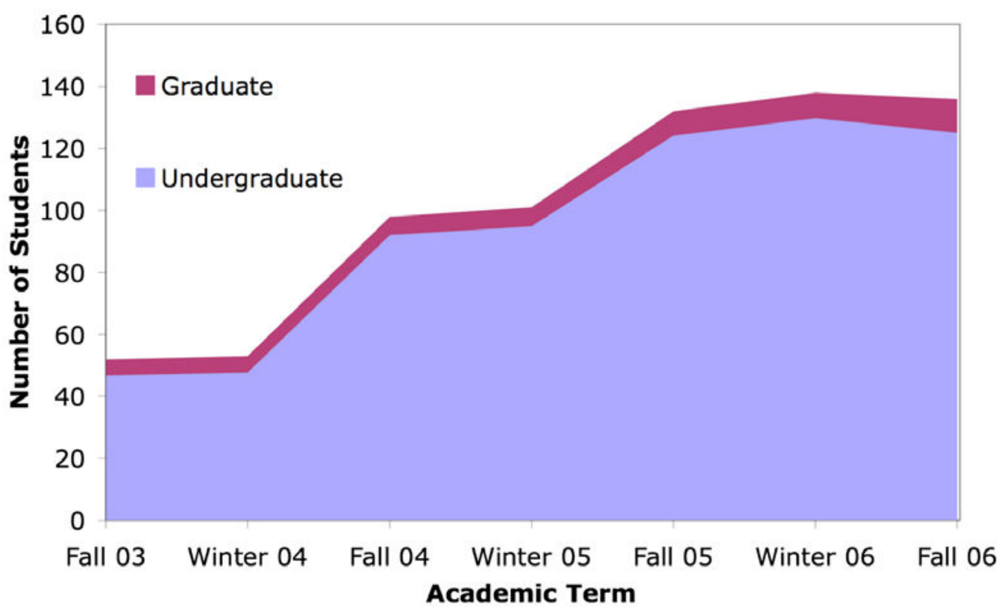

Figure 2: *S3FL membership from 2003-2006.*

This rise in student membership corresponded with a shift in S3FL's approach in the wake of numerous university space systems projects being shelved following the in-flight breakup of Space Shuttle Columbia in 2001. Rather than focusing on a single top-tier project and risking its cancellation due to external factors beyond the lab's control, S3FL opted to protect itself by incorporating a number of introductory and mid-tier projects as well as participating in various competitions. For example, the can-sized CanSat payloads are used as less complex and low-cost projects to introduce younger students to S3FL objectives and processes while training them for future participation in top-tier projects. Successes and publicity generated from these projects, including S3FL's first-place finish at the 2005 CanSat Competition, stimulated interest in the lab and contributed to its rapid growth. The following adaptations have been undertaken by the lab to handle the population boom.

2.1.1 Expanded academic offerings

To accommodate the influx of lab members seeking to earn course credit, S3FL has expanded its course offerings and has helped introduce an entry-level course. Table 2 shows the ways in which students can directly earn credit for S3FL work, ranging from introductory classes to technical electives to graduate directed study. Efforts are also underway to enable students to earn a practicum distinction on their academic transcripts through S3FL participation.

Technical Electives	
Aerospace Engineering	AERO 390, 490
Atmospheric, Oceanic, & Space Science	AOSS 280, 381, 990
Electrical & Computer Science Engineering	EECS 499, 599
Research Programs	
Undergraduate Research Opportunity Program	UC/ ENGR 280

Table 2: *Credit options for S3FL work for 2006-2007 academic year.*

An entry-level course has also been introduced to simultaneously acclimate students to space systems engineering being promoted in S3FL but also to meet the programmatic requirements of all College of Engineering undergraduate degree programs. This course, ENG 100-700, is not formally part of S3FL but was introduced to allow students to meet degree requirements, institutionalize facilities and commitments associated with design-build-test activities, and provide first-year students with the training necessary to participate in upper-level projects.[13]

2.1.2 Upgraded lab facilities

S3FL's primary facilities are located at the University of Michigan's Space Research Building. In previous years, S3FL's main office and lab space were housed in two separate, relatively small rooms. Due to S3FL's growth, the lab and its faculty advisors worked with the AOSS department to obtain larger accommodations. Not only will the new lab space be able to meet current S3FL administrative and lab needs, it will allow for additional workbenches to meet future demands. The upgraded facilities include an office area for administrative tasks and teleconferences, a dedicated file and web server, a soft-wall cleanroom for integration and testing of sensitive flight hardware, and a fume hood and ceiling vents for wet chemical work and soldering. Each project housed in the new lab will eventually have a dedicated electronics workstation for prototyping and testing of electrical components. Computers at each workbench will support ground testing as well as command and data handling programming needs.

In addition to its primary facilities, S3FL has secured secondary lab facilities in the AERO Engineering Programs Building (e.g., wind tunnel testing, hardware assembly, etc.) and the Wilson Student Project Center (e.g., metal prototyping, computer numerical control machining, etc.) along with other engineering student groups. Vacuum and thermal chambers, radio-frequency antenna test equipment, and vibration test setups, which are not present in S3FL facilities, may be accessed via the AOSS Space Physics Research Laboratory (SPRL), the EECS Radiation Laboratory, and the ME Vibrations and Acoustics Laboratory, respectively. Design and documentation efforts are aided by access to the Computer Aided Engineering Network, including modeling, analysis, and computer-aided design (CAD) software. In recent years, S3FL has collaborated with the Michigan Aeronautical Science Association (MASA) student rocketry group to make use of composite fabrication facilities. These additional resources augment S3FL's own capabilities and improve the support of a wider range of projects.

2.1.3 Enhanced communications and documentation infrastructure

Good communications and documentation is crucial for timely dissemination of information and avoidance of past mistakes. Weekly team meetings and project email lists are the primary modes of communication in S3FL, and an email newsletter, *The S3FL Observer*, provides all lab members with project updates, upcoming lab events, and important deadlines. A Standard Operating Procedures (SOP) manual, detailing the lab's policies and processes, is updated at the beginning of every academic term and made required reading for all lab members. This SOP manual allows for consistent handling of administrative issues among the different project teams.

S3FL has set up a bulletin board page on the University of Michigan's CTools website to enable its members to electronically post and access project files, with the team leads acting as moderators. CTools thus facilitates document sharing, lessons learned, and configuration management among team members, and it provides live chat capabilities useful for real-time collaborative efforts. For large CAD and analysis files, S3FL's file server is used to provide storage and file sharing. Efforts are underway to migrate the server to a university-supported network to improve data transfer rates and obtain server backup capabilities.

To help consolidate and streamline personnel information, the lab is debuting in 2007 the S3FL Information Management System (SIMS). A S3FL server is hosting a reliable open-source database that can be accessed through the Internet by using an open-source HTTP server. The system provides S3FL members with useful information and a history of their work within the laboratory. When students with "Engineer" classifications log into SIMS, they are presented with information about official S3FL records as follows:

- General information: year, major, S3FL start date, gender, associated organizations, special engineering skills, etc.
- Current term information: member classification, class enrollment and status, and associated projects

- Certifications and awards: standard certifications (e.g., Occupational Safety and Environmental Health certificates of safety), machine shop safety certifications, S3FL Most Valuable Engineer recognitions, etc.
- Events: regular team meetings, outreach activities, formal design reviews, workshops, etc.
- Attendance: events and meetings
- Outreach: internal and external events, S3FL promotions, conferences, etc.
- Comments from S3FL community: public bulletin board where any member of S3FL, including team leads, Excom members, and faculty advisors, can leave feedback for the student
- Hours and weekly reports: log of weekly work hours and description of action items completed

Team leads have a similar home page, but in addition they have the option to manage group information. For Excom members, they may also view snapshots of all the worked hours by lab members.

2.2 Maintaining effective project leadership and technical expertise

During a fall academic term, S3FL typically welcomes about 60-70% of its population as new members, the majority of whom are first-year students. These new members are recruited through informational sessions, strategic hiring efforts, and word-of-mouth advertising. Table 3 shows the demographics for the 2006 fall term. As with any student organization, S3FL must deal with the challenges of student retention and turnover; in particular, top-tier projects must face the prospect of experienced team members graduating or leaving the lab prior to project completion. Retention rates between the fall and winter academic terms are greater than 90%, allowing a high level of continuity through a one-year design cycle. However, the turnover of upper-level students is unavoidable, particularly due to graduation at the end of the academic year. To sustain project progress and continuity, S3FL provides a strong in-house training and mentoring system that prepares less experienced students to take over the responsibilities of departing team members.

Number of academic terms in S3FL	
1	61%
2	13%
3	9%
4	10%
5 or more	7%
Membership type	
General member	77%
Team lead/ assistant lead	17%
Excom	6%

Table 3: *S3FL personnel statistics for 2006 fall term.*

2.2.1 "See one, do one, teach one" paradigm

About 20-30% of the students remain active in S3FL beyond their first year, and these students are the ones that generally fill team lead positions. Promising candidates who desire to take on more responsibility are identified early on by team leads and Excom advisors. These students are then steered towards assistant lead positions. By shadowing and working closely with experienced team leads, these students learn to adopt a systems engineering mentality that emphasizes sound engineering trade studies, rigorous requirements traceability, and meticulous interface control. They also learn to plan project schedules and budgets with contingencies, handle team personnel conflicts, and manage setbacks such as unanticipated requirements changes, procurement delays, or failed ground testing.

When candidates become comfortable with the responsibilities of leading a small team, they are given lead status by Excom when such positions open, and they begin mentoring their own team members. Thus, S3FL's "see one, do one, teach one" paradigm is fulfilled, as a student is able to observe and learn from the actions of a lead, then take on a leadership role, and in turn pass on the experience and knowledge gained to the next generation of team leads. In a similar manner, qualified candidates are groomed by existing Excom members for eventual Excom membership through a series of leadership roles of increasing responsibility. Such mentoring of new lab members encourages senior students to take an interest in the development of younger students and allows S3FL to sustain itself.

2.2.2 Workshops and weekly seminars

Given the high percentage of first-year students beginning to enroll in S3FL, a surplus exists of creative, energetic students without a background in engineering or space systems. In order to maintain the interest of incoming students, ease the burden on team leads, and increase the general knowledge level of the lab, senior students in S3FL have begun holding workshops and training sessions. For electrical subsystems, these sessions cover circuitry, microcontroller programming, operational amplifiers, transistors, and computer simulation of circuit responses. Some of these workshops have been held in usual teaching labs, such as the ENG 100-700 facilities. Training is also provided for micro-soldering components with small and closely spaced pins. Workshops for mechanical and structural subsystems include machining skills and safety, as well as CAD courses for modeling and simulation. These workshops build necessary skills for the associated subsystems while encouraging cross-subsystem knowledge and understanding of potential integration issues. Teaching these topics in conjunction with design projects further enhances familiarity with practical engineering applications and quickly builds a talent base of students who can contribute positively to their projects. Creating the curriculum for the workshops and training sessions has also served to formalize the body of knowledge available to S3FL students.

To facilitate the transmission of knowledge and lessons learned among S3FL project teams outside of formal design reviews, a series of weekly seminars was initialized for the 2006 fall term. These hour-long seminars provide an opportunity for all S3FL students to meet for presentations and discussions, regardless of project affiliation. Two seminar formats are used. The first format has student leaders present lessons learned from past S3FL projects or lecture on general space systems engineering and design skills. The second format has students present on current issues facing their teams. This method allows for a communal review and critique of design approaches with senior, experienced lab members and faculty. The seminar is also held during usual working hours, unlike most S3FL events, to allow greater participation of interested students, faculty, and staff.

2.3 Securing external support

S3FL has enjoyed support from the University of Michigan's College of Engineering, and it has also had a fruitful relationship with SPRL, whose professional engineers are valuable mentors who offer critiques at design reviews and provide guidance with test setups, hardware design, and software coding. A strong S3FL alumni base, with members in government, industry, and academia, are a ready source for technical advice and project opportunities. As an expanding lab with a growing number of projects and corresponding operating costs, however, S3FL also needs to look at other external sources of support to meet its financial and equipment needs.

2.3.1 Principal sponsors

Lockheed Martin Corporation is one of the main sponsors of S3FL and has continued to provide technical advice, equipment donations, and financial support throughout the years. Top-tier S3FL projects generally coordinate their design reviews to correspond with on-campus visits by Lockheed Martin engineers, who are available to serve as reviewers. When difficult technical issues arise, S3FL has submitted questions to Lockheed Martin, where they are circulated among a group of experienced engineers. Advice from these engineers, with their wealth of practical experience, is invaluable to S3FL project teams.

The Michigan Space Grant Consortium (MSGC), which fosters awareness of, education in, and research on space-related technology in Michigan, supports the work of individual S3FL students via undergraduate and graduate research fellowships. In addition, MSGC has also undertaken larger initiatives to assist S3FL efforts. In 2004, MSGC administered the Space Engineering Experience Diversity (SEED) Scholars Program, which provided funding for a group of underrepresented minority engineering students to spend the summer working on S3FL projects. In 2006, MSGC was awarded funds for the Michigan Initiative on Student NASA Exploration Research (MISNER) program, part of which is funding S3FL's 2007 CanSat teams in the interest of workforce development.

2.3.2 Proposal writing and solicitations

For top-tier projects, S3FL students assist faculty advisors with proposal writing to secure funds, technical support, and launch opportunities. Proposal writing exposes students to a critical aspect of industry and research. They learn to rapidly design a top-level system and architecture, to write in the unique proposal style, and to work in the fast, deadline-driven pace that is required.

In addition to proposal writing, S3FL students also engage in direct solicitation for money and in-kind donations (i.e., a product for free or at an advantageous discount). A good case study is presented by S3FL's MClimber team, which entered a beam-powered space elevator climber prototype in the Spaceward Foundation's Elevator: 2010 competition.[14] Not only did the team need to obtain components such as motors, solar cells, and the beam power source, but the team also had to secure funds for fabrication, services, and travel to the competition site. Hence, the team mobilized a fund-raising effort, with a group of students assigned the task of contacting and following up with companies. Guidelines and tips from more experienced lab members were presented at the beginning of the campaign, with regular feedback and follow-up to motivate and assist students in their task. A sponsorship packet was designed and sent off to potential sponsors, explaining the benefits of sponsorship such as publicity, tax write-offs, and student recruitment opportunities. Also, a sponsor database was created and made available to all team members to document and direct the fundraising effort. Donations from the months-long campaign were able to cover most of the team's travel and equipment needs. Owing to their successful fundraising, the MClimber team was able to travel to and compete in the 2006 Elevator Games in Las Cruces, New Mexico.

2.3.3 Publicity and outreach

In order to better publicize the work and projects at S3FL, current and past project information is available at the lab's website (http://data.engin.umich.edu/s3fl). When a project team is involved in a design competition, daily updates are provided on the website to keep lab members and sponsors informed of the team's progress. The website is particularly helpful as a reference when recruiting new lab members or soliciting companies for donations. Significant achievements by the lab, such as winning competitions, are announced in departmental and university publications.

Outreach is a requirement of participation in S3FL and has led to a very robust and expansive effort in the lab. These events provide a way to publicize the lab on campus and allow lab members to share the fun and excitement of mathematics, science, and technology with pre-college students. Activities, frequently in collaboration with MSGC and other campus organizations, include hands-on projects, lab tours, and presentations of project experiences. Brief classroom lectures are sometimes included to instruct younger students on rocketry, aerodynamics, blimps, and presentation skills, which are then applied to group activities. Such "beyond the formal classroom" learning experiences promote the aerospace field to elementary, middle, and high school students and encourage them to pursue higher education in engineering and the sciences.[15] The outreach effort has also resulted in the active participation of S3FL students in the development and prototyping of the ENG 100-700 course; indeed, S3FL students form the backbone of the volunteer corps that help run the course's design-build-test competitions.

3 Lessons learned for managing student projects

Since the formation of S3FL, generations of students have compiled technical and administrative wisdom regarding their experience with S3FL projects. These lessons are critical to avoiding oft-repeated mistakes. Some of the most significant lessons learned regarding the management of student projects include the need to promote and communicate interdisciplinary awareness and systems perspective, to account for the realities of a student workforce, and to manage in a proactive, vigilant, and responsible manner.

3.1 Promote interdisciplinary awareness and systems perspective

In relatively complex, top-tier projects like TSIX (Tethered Satellite Ionospheric eXplorer, a tethered nanosatellite pair for ionospheric characterization and a validation testbed for on-orbit rendezvous and formation flying sensors), where a large team of thirty or more students is split up into subsystems, it may be easy for team members to develop tunnel vision. Students may become so consumed with optimizing their own subsystem's design that they fail to recognize the critical impact that their engineering decisions have on other subsystems. Interfaces between subsystems may be neglected, causing grief later in the design cycle. Thus, it is important for the lab to develop students as team players comprehending the consequences that their design trades have on the rest of the project.

In S3FL, dedicated systems engineering roles and concurrent design meetings (CDMs) promote structured, regular interactions among subsystems. Experienced students seeking to broaden their perspectives beyond a single technical discipline may take on systems engineering roles to facilitate inter-subsystem interactions and work to identify and resolve issues that span multiple subsystems. At CDMs, all subsystems of a project are brought together. These industry-inspired technical meetings provide a real-time environment for all subsystems to work together and address interdisciplinary issues such as ownership of interfaces, systems requirements flowdown, risk mitigation, and integration troubleshooting.

To facilitate the transfer of interdisciplinary knowledge to younger students, senior lab members are asked to be reviewers and to focus on systems-level concerns at the design reviews of introductory and mid-tier projects. Where logical to do so, inter-project collaboration is also encouraged between a top-tier and a smaller project, which can act as a prototype testbed for the top-tier project to mitigate development risk. Increased mentorship of younger students occurs because the top-tier project now has a stake in seeing the smaller project become successful. One such example is the 2006 C-9 team successfully testing a functional prototype nanosatellite separation system for TSIX (at the time named TSATT for Tethered SATellite Testbed), in a microgravity environment.[16]

3.2 Account for student workforce realities

The management of student teams is a unique challenge with a number of differences when compared to similar enterprises in industry. The academic cycle provides a rhythm to the annual schedule with a predictable dearth of activity around midterm and final exam weeks. A reduction in personnel is typical during the summer months due to students departing for home and summer work, but the remaining team members are capable of more focused activity. Also, the turnover rate of personnel due to graduation or increased course loads is a concern for knowledge retention and leadership continuity as the most experienced students depart. S3FL teams have adapted to these risks by scheduling important milestones and deliverables away from academic conflicts, augmenting the summer workforce with visiting research students, and implementing an extensive mentoring program.

S3FL must also address issues with its diverse membership, in which over a dozen countries are represented. Care must be taken to ensure the lab's compliance with the International Traffic in Arms Regulations (ITAR), which restricts non-U.S. citizens from accessing and exporting defense articles and services. For cases in which the ITAR status is not clear, S3FL seeks clarification or a waiver from the U.S. State Department. Non-U.S. students are informed upon joining the lab that certain projects or aspects of projects are unfortunately off-limits to them due to ITAR, and sensitive equipment is kept locked with limited-access keys. Use of such equipment is carefully monitored via check-in and check-out protocols, and it is kept under assigned surveillance when transported in public.

Finally, contrary to some popular opinion, student-designed and built flight hardware does incur significant costs. S3FL has learned that securing external funds is a crucial part of successful student endeavors. Maintaining a disciplined and effective fundraising team is a proven way of providing the capital required for a sustained and stable program. Unfortunately, students who are expected to pull double duty as both engineers and fundraisers have historically tended to focus on engineering work to the detriment of fundraising efforts. Thus, a dedicated business team has been proposed with a focus on fundraising. Such a setup would consolidate existing, project-level fundraising teams into a lab-wide team, thus expanding the pool of beneficiaries and reducing the number of inefficient instances of lab members independently contacting the same company. In addition, the fundraising effort may be decoupled from the engineering schedule, and entry-level positions for fundraisers would be created in the lab where students who lack the technical expertise to provide detailed engineering support can still contribute to the lab while being trained in the necessary technical skills.

3.3 Manage effectively

Over the years, Excom and team leads have identified effective solutions for management and oversight of the various S3FL projects. Chief among these solutions is the creation and implementation of an effective schedule. To be effective, a project schedule must be aggressive yet reasonable, with binding consequences.

An aggressive schedule is one that is sufficiently advanced to produce a design concept early on with adequate time for testing. Time and time again, ideas that looked good on paper have exhibited troublesome nuances that hinder physical implementation. Machinability, assembly procedure, mechanical tolerances and clearances, and interactions among components and subsystems can lead to problems difficult to anticipate prior to the prototyping or integration of a product. Such problems are especially evident with students inexperienced in the practical arts. These unknown but predictable problems can be countered with many weeks or months of scheduled testing and integration. An aggressive schedule also takes advantage of the transformation of students and teams as they learn, bond, and grow in technical knowledge and maturity. Previously uninterested students become motivated by small successes, and those who entered the program without prior training become technically adept. The project manager must be willing to challenge the team and motivate the team members to rise to the occasion; allowing for the growth of students should be a goal of the project and not merely an afterthought.

A reasonable schedule is one that accounts for the aptitude of the students involved, the budgetary limitations of the project, and the external distractions (e.g., exams, vacation times, etc.) present in an academic setting. It is the counterpoint to an aggressive schedule, and it forces a prioritization of activities in light of the relative scarcity of resources. Frequent, smaller goals tend to lead to greater accomplishments than one large push at the end of a project. If the work is divided up throughout the course of the project as discrete deliverables, the team becomes more productive rather than procrastinating until the end. Having milestones early in the project allows managers to gauge the team's aptitude and accelerate the team-forming process while allowing more time for mid-course corrections to be applied.

A binding schedule is one that involves real consequences if certain milestones are not reached. Funding incentives are ways of linking consequences to milestones positively. For instance, leading up to the 2006 CanSat Competition, S3FL held an internal competition amongst its three separate design groups. An impressive round of activity ensued, since the team with the most feasible design and highest potential for success was given additional resources in the form of a test launch aboard a MASA rocket. Milestones in the form of external design reviews and system demonstrations, with the prospect of embarrassment for a poor showing, can be effective motivators for a successful performance.

Figure 3: *MClimber at the 2006 Elevator Games was one of four teams out of 20 entrants to reach the top of the 55-m ribbon.*

At times, imposing hard deadlines in the form of gateway milestones becomes necessary. Gateway milestones must be successfully met to ensure the continuation of the project. An example of implementing such a strategy is the MClimber project in 2006. As the behind-schedule project was approaching the competition date with a real risk of not achieving an adequately functional climber robot, Excom decided that a successful demonstration of the MClimber system under competition conditions would be a prerequisite for releasing the budget for travel and other competition costs. As expected, this decision prompted an impressive effort by the entire lab in which resources from across S3FL were drawn to fix the technical problems plaguing the climber robot. At the end of the three-week period, the team had a functional robot and was permitted to attend the competition. As seen in Figure 3, the MClimber team performed well, becoming the first team in history to climb to the top of the competition ribbon solely under beam power. The pressure of a self-imposed deadline, combined with the dedication and ingenuity of S3FL students, saved the day. Similar gateway milestones have since been imposed on other S3FL projects earlier in the project timetable to provide adequate schedule margin.

Conclusion

S3FL's founding purpose was to provide university students with practical, hands-on experience through design-build-test activities of space systems. As a student-run lab, it faces distinct administrative and logistical challenges of accommodating growth, sustaining technical and managerial competence, and securing support for personnel and equipment for continued operations. Since 1998, S3FL members have tackled these problems with ingenuity and persistence. Over the years, the lab has supported over a dozen projects that have generated student enthusiasm for the space systems engineering field and trained hundreds of students in technical, teamwork, communications, and management skills. Lessons learned in managing a student workforce have been readily incorporated within S3FL's operating philosophy, as the lab seeks to improve its capability and effectiveness in carrying out its mission. This lab activity has been a positive influence not only on the participants, but also as an agent of constructive change in the curriculum.

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