AC 2007-1442: MICROGRAVITY FLIGHT TESTING AS A CASE STUDY ON THE STUDENT SPACE SYSTEMS FABRICATION LABORATORY

Ashley Smetana, University of Michigan
Undergraduate Student, Aerospace Engineering

Thomas Liu, University of Michigan
Graduate Student, Aerospace Engineering

Suzanne Lessack, University of Michigan
Undergraduate Student, Aerospace Engineering

Rebecca Wind, University of Michigan
Undergraduate Student, Aerospace Engineering

William Woelk, University of Michigan
Undergraduate Student, Aerospace Engineering

Theresa Biehle, University of Michigan
Undergraduate Student, Aerospace Engineering

Laura Dionisio, Loyola Marymount University
Undergraduate Student, Electrical Engineering

Nathaniel Gallaher, University of Michigan
Undergraduate Student, Electrical Engineering

Katie Thorne, Michigan Technological University
Undergraduate Student, Physics

Rafael Ramos, University of Michigan
Graduate Student, Space Science

Brian Gilchrist, University of Michigan
Professor, Electrical Engineering and Space Science

Peter Washabaugh, University of Michigan
Associate Professor, Aerospace Engineering

Microgravity Flight Testing as a Case Study on the Student Space Systems Fabrication Laboratory

Abstract

As a student-run organization, the Student Space Systems Fabrication Laboratory (S3FL) provides over a hundred undergraduate and graduate students each year with the opportunity to work on real-world, design-build-test space systems projects. Such opportunities include the microgravity flight experience available through NASA's Reduced Gravity Student Flight Opportunities Program. By having a proposal accepted through a competitive evaluation process, students can design and fabricate an experimental payload that flies onboard a C-9 plane whose parabolic flight trajectories permit short periods of microgravity test conditions.

During August 2006, S3FL flew a C-9 microgravity test payload in support of the lab's Tethered SATellite Testbed (TSATT) project, now known as the Tethered Satellite Ionospheric eXplorer (TSIX) satellite. In accordance with the 2004 Presidential Commission Report that realigned NASA's objectives, TSATT is a tethered nanosatellite mission for demonstrating the feasibility of a tethered satellite system as a suitable platform for validating rendezvous and formation flying sensors and algorithms. Once released from the launch vehicle, the initially joined end masses will separate from each other while remaining connected by a high-survivability tether. Through use of a variable-length tether deployer and retriever, sensor performance at multiple, controlled nanosatellite separation distances can be tested. Also, the nanosatellite pair provides well-defined, close-flying passive targets for long-term tracking and calibration of ground-based sensors for space situational awareness applications.

To ensure mission success, S3FL is validating as much of the system design as possible through prototyping and ground testing. Since separation of the nanosatellite pair is a potential single point of failure for the TSATT mission, the functionality of the in-house designed separation mechanism must be validated prior to the actual mission. A C-9 flight permitted such a test in a zero-gravity operating environment, and it also provided an opportunity to record end mass dynamics at separation for different system tumbling conditions. This data will be useful for refining predictive dynamics models for the TSATT mission and future tethered space systems.

This paper discusses the S3FL C-9 Tethered Satellite Dynamics at Separation Investigation Team's (TSSIT) design-build-test experience from project conception and requirements definition through flight testing and post-flight redesign work. In particular, the paper evaluates how the C-9 project enabled S3FL students to apply classroom knowledge in a real-world, interdisciplinary setting, to experience working through a complete design cycle, and to develop a systems engineering mindset.

1.0 Introduction

The Tethered SATellite Testbed (TSATT), currently being developed by the University of Michigan's Student Space Systems Fabrication Laboratory (S3FL), is being designed to evaluate formation flying and automated rendezvous and docking sensor technologies. The main purpose of TSATT is to develop a way to decrease the risk normally incurred while testing these sensor technologies and algorithms in flight as well as to develop ground observation capabilities of close-flying spacecraft. The design of TSATT consists of two end masses – connected by a tether developed by Tethers Unlimited, Inc. – that are initially joined together. Upon separation, the end masses are free to move apart from each other as the tether is deployed up to 1 km. Deployment initiates the beginning of data collection from the two end masses. Once a set time is reached, the tether begins to retract, and data is collected as the two end masses are pulled together.

Since separation is a possible point of failure on the TSATT system, the Tethered Satellite Dynamics at Separation Investigation Team (TSSIT) was formed to investigate the performance of the separation mechanism in a zero-gravity operational environment. The S3FL in-house design incorporates pin pullers locking the two end masses together until a timing circuit actuates the pin pullers and releases the two halves. Upon release, the end masses are free to separate, the dynamics of the tether between them can be observed, and various rotational dynamics can be recorded. In order to quantitatively evaluate the system, the team used three cameras to capture the motion of the end masses during the zero-gravity periods. This data, along with measurements taken by the Inertial Measurement Units (IMUs), were used to validate if mission objectives were met and if the system performed as expected. Based on the preliminary results of the team's microgravity flight, recommendations have been made to modify the separation mechanism design so that better performance can be achieved at separation. This paper discusses not only the project, but also the laboratory structure, outreach activities, and lessons learned throughout the project.

2.0 Laboratory Background

TSSIT is part of the Student Space Systems Fabrication Laboratory (S3FL)[1], a student-run lab in which undergraduate and graduate students of all academic disciplines have the opportunity to work on space systems projects. The lab is organized in a pyramid type structure, with faculty advisors and the student Executive Committee (Excom) overseeing all projects and acting as mentors to the project leads. Within each project team, there is a student chief engineer, a project lead (occasionally the same person as the chief engineer), an assistant lead, and several subsystems. If the subsystems are large enough, they will have their own subsystem leads. This organization allows for the younger students to learn from more experienced students in lead positions using the "see one, do one, teach one" method of passing on knowledge within the lab.

2.1 S3FL objectives

The lab allows students to apply their classroom knowledge to hands-on, interdisciplinary projects while working through the complete design cycle and developing a systems engineering mindset.[2] The goal of the lab is to make students wiser engineers to better serve as the nation's future aerospace industry work force. This is done by offering students the opportunity to work on design-build-test projects in which they are able to participate in all aspects of spacecraft and mission design.

2.2 Previous C-9 projects at the University of Michigan and in S3FL

The C-9 Reduced Gravity Flight Opportunities Program[3] has been offering zero-gravity flights for undergraduate students nationwide for 10 years. In the 2005 flight season, a switch was made from the KC-135 to a newer C-9 aircraft, in which a series of 30 parabolas are performed over the Gulf of Mexico on each flight. At the top of the parabola, the experiments and flyers in the plane experience microgravity for approximately 20 to 25 seconds. Student teams are required to write a proposal that goes through a competitive selection process. Once selected, a team has flight crew deadlines and also a Test Equipment Data Package document to submit before traveling to Houston for flight. Once at Ellington Air Force Base at NASA's Johnson Space Center, the team must participate in a flight readiness review before receiving the "go" for flight. The team's time in Houston includes tours of Johnson Space Center, physiological training, and daily briefings along with two flight opportunities.

As part of the S3FL's start-up efforts in 1997, a group of students developed a KC-135 project that eventually flew on the Space Shuttle Endeavour missions in January and then December 1998. This small, self-contained payload was the Vortex Ring Transit Experiment (VORTEX)[4], and it investigated vortex ring interactions with fluid interfaces in microgravity. In 2002, another KC-135 project known as THIRMA (Thermally Induced Refraction in a Microgravity Atmosphere)[5] was flown. The basis of this project was to characterize the refractivity of light through air in a microgravity environment. This was done in order to help with the development of space telescopes that could use lightweight, temperature-controlled "gas lenses" instead of the typical heavy mirrors. The successes of both VORTEX and THIRMA helped motivate the TSSIT microgravity experiment.

3.0 TSSIT C-9 Project

Beginning with conceptual planning in August 2005, the microgravity project to validate TSATT's separation system concept involved over two dozen S3FL students as designers, analysts, machinists, flight crew, ground support, and advisors. The experiment proposal was submitted by students to NASA in October 2005 and accepted that December. The project is expected to last until April 2007 with completion of flight data analysis. Table 1 outlines the major project milestones.

3.1 Design-build-test project for undergraduates

Based on the successes of previous C-9 (KC-135 prior to 2006) flights, S3FL was interested in flying key components of a larger lab project to gain insight on performance capability and design validity. C-9 projects are also appealing in that they are good opportunities to fly hardware that has been designed, built, and ground-tested by students. Students who have the chance to fly return to the lab very motivated and with a unique perspective that they can pass on to other students who have not had such experiences.

Milestone	Date
Project Definition Phase	
Letter of Intent and Proposal	October 2005
Mission Definition Review (MDR)	November 17, 2005
Announcement of Flight	December 9, 2005
Design Phase	
Preliminary Design Review (PDR)	February 20, 2006
Flight Team Selection & Flight Physicals	May 1, 2006
Test Equipment Data Package	May 31, 2006
Evacuation Plans and Badging Requests	June 21, 2006
Testing/Operations Phase	
Fabrication Completed	July 15, 2006
Ground Testing Completed	July 30, 2006
S3FL “Go” Decision Granted	July 30, 2006
Flight Week	August 10-19, 2006
NASA Report Due[6]	October 13, 2006
Final S3FL Report Due	April 2007

Table 1: TSSIT project milestones.

In the summer of 2005, S3FL Excom decided that a validation test of TSATT’s in-house designed separation system was necessary. Because this system could be a single point of failure in the TSATT design, it was desirable to perform validation tests in a microgravity environment. Figure 1 shows the computer-aided design (CAD) model of the separation system and the flight hardware tested in microgravity.

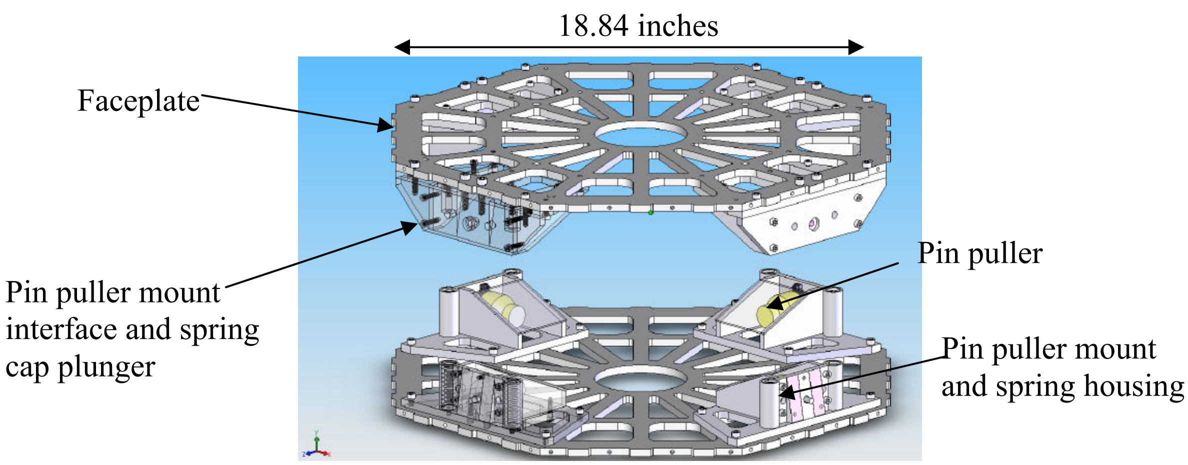

Figure 1: CAD model of separation mechanism and face plates (previous page). Prototype design being tested in microgravity (above).

3.2 Lab, University, and external collaborations

Within S3FL, the C-9 projects often test concepts planned for future or current projects in the lab. Teams occasionally work with senior design teams from the aerospace or mechanical engineering programs to address certain aspects of the design and testing of a system. The teams are under the supervision of faculty advisors and Excom, who provide guidance and points of contact for external collaboration and resources. TSSIT had its electrical components developed in S3FL's Power and Electrical Lab, which also housed the clean room where flight-rated components were stored. Raw materials and unfinished parts were stored in dedicated lab areas, and the team was also allowed access to a faculty advisor's teaching lab for integrated testing purposes.

Funding and resources for the project were provided from various sources. Travel costs were reimbursed through a grant provided by the Society of Women in Science and Engineering (WISE) and an undergraduate research fellowship from the Michigan Space Grant Consortium (MSGC). Two important flight components, the pin pullers and the tether deployer, were donated to the team for use during flight. The pin pullers were received from a cancelled NASA ProSEDS (Propulsive Small Expendable Deployer System) project in the University of Michigan's Space Physics Research Laboratory. The tether deployer and the tether were donated by Tethers Unlimited, Inc. (TUI) as a collaborative effort with TSATT to study tether dynamics between tethered end masses during separation.

3.2.1 TSATT

Since TSSIT was to validate the separation concept and prototype mechanism for TSATT, the two teams worked closely together to ensure the C-9 tests were relevant. The mission objectives for TSSIT were created by the TSATT chief engineer and mechanisms subsystem and evolved along with the TSATT project. The TSATT structures and the electrical subsystem leads aided with the structural and electrical designs and constraints, respectively. Regular meetings between the two teams and participation at each others' technical design reviews helped to reduce instances of miscommunication where changes to TSATT were not translated to the C-9 team in a timely manner.

3.2.2 Mechanical Engineering (ME 450) class

Several students within S3FL designed and constructed the first prototype separation system as part of a senior design class that fulfilled an academic course requirement in the College of Engineering. Over the course of the semester, the mechanical engineering student team worked closely with members of TSATT, the C-9 team, and faculty members to develop a plausible design.[7] The ME 450 team worked with the S3FL Machining team to fabricate the design and with the C-9 team for component and integrated systems testing. The end result was a working prototype that satisfied the structural, material, and manufacturability constraints provided by the various teams.

3.2.3 S3FL Machining team

To maintain a close relationship with the S3FL Machining team, a TSSIT team member worked directly with them as the TSSIT representative. This reduced the lead time for machining the parts, since questions that arose during the fabrication and assembly process could be promptly answered. The relationship also benefited the C-9 project in that the Machining team's members were able to suggest improvements that contributed to the final design of the end masses. The Machining team made use of the equipment available in the Wilson Student Project Center, including Computer Numerical Control (CNC) machines, lathes, drill presses, and assorted saws and hand tools, to complete the fabrication of hardware for flight.

3.2.4 Summer research students

As part of the Research Experience for Undergraduates (REU) program, many departments at the University of Michigan offer students summer research positions. S3FL typically accommodates a few students each summer for its projects. TSSIT was working under tight deadlines while preparing for flight in the summer of 2006, and the REU students, who had experience in electrical engineering and physics, were major contributors during the integration and testing phases of the project. Without their help, the project would have been under-staffed due to students leaving town during the summer months, and the project would have had a difficult time meeting the deadlines necessary for flight.

3.2.5 S3FL faculty advisors

The faculty members within S3FL are valuable resources for the students and fulfill many roles. Specific to TSSIT, they provided technical insight regarding the system design and offered advice on the testing plan in order to gain as much as possible from the microgravity experiment. While they did not provide detailed plans to solve problems, they pointed the team members in the right direction to arrive at solutions on their own. The faculty advisors ensured that students remain on track via weekly meetings with team members. This allowed the students to consistently improve the design of the system until it effectively met all project requirements. Periodically, the team was required to present design reviews on the current status of the project for the faculty advisors as well as members of S3FL. These design reviews served as a formal way to inform faculty members of all aspects of the project and provided a forum where the reviewers could provide constructive criticism to the students to facilitate project success. Design reviews also allowed members from TSATT to see how the C-9 aspect of the project was progressing and made sure that the objectives and requirements were compatible between the two teams.

3.2.6 S3FL Executive Committee (Excom)

The members of S3FL's Excom, composed of upper-level S3FL members who have had years of project lead experience, fulfilled the upper-level administrative role in TSSIT. It was their task to ensure close coordination between the teams as well as making the final go/no-go decision. During the course of the design process, members of Excom evaluated the direction of the project and determined whether it was aligned with TSATT's goals and objectives. The members of Excom also provided valuable technical help and made themselves available resources to the TSSIT members. This was especially important during the testing phases in which some students did not have much practical experience, so the Excom members were able to step in and provide support for the team.

3.2.7 Tethers Unlimited, Inc.

An integral part of the separation system was the tether deployer technology used in the end masses. In collaboration with Tethers Unlimited, Inc. (TUI), TSSIT was granted use of a tether deployer and tether similar to that being proposed for the TSATT mission. Along with the primary objective to validate the separation mechanism concept, a secondary objective of TSSIT was to capture data on the movement of the end masses during tether deployment. Through a combination of Inertial Measurement Unit (IMU) data and video recording, the team was able to capture and analyze the deployment motion of the end masses under different orientations and spin rates. This information was useful to TUI for development research but also to future projects in S3FL that may employ this tether deployment technology.

3.2.8 Lockheed Martin

The separation mechanism design was subject to many levels of constructive criticism throughout the design cycle. Beyond internal reviews, TSSIT and the ME 450 design teams went through many reviews with Lockheed Martin, a principal industry sponsor of S3FL. In these reviews with Lockheed Martin engineers, the system was critiqued according to industry standards. The team was given insight into the issues that concern engineers in industry, and the team also benefited from suggestions on how to improve the system and make the design more robust.

3.3 Flight results

Based on the data analysis that has been completed so far, the team has been able to draw a number of important conclusions. The separation mechanism was successfully demonstrated 32 times under a number of different tip-off conditions in microgravity, and video data (~100 GB of total test data) of the flight permitted observations of the motions of the end masses. Listed in Table 2 are the primary and secondary mission objectives accomplished during the project.

From observations made during flight, it was determined that changes need to be made to the separation mechanism design to improve its performance. In particular, the design needs to have "guides" that direct the motion during the period when the springs are acting on the end masses to impart the separation force. This will keep the end masses from rotating in a manner that would be considered independent tumbling, resulting in tether snag around the end masses. IMU data was collected from the end masses to support the observations and is currently being analyzed for use in a dynamics model that will predict the motion at separation. During flight testing, a pin puller malfunctioned and contingency troubleshooting plans were executed to try and correct the anomaly. Although the pin puller was unable to be repaired during flight, a spare pin puller that was qualified in ground testing replaced the damaged one and permitted the successful resumption of flight tests.

Objective	Ground Testing	Flight Testing
Primary		
Test and validate, in microgravity under different tip-off conditions, the concept of the TSATT separation mechanism		√
Collect end mass separation data to validate predicted dynamics model of the system		√
Secondary		
Develop handling, test, and integration procedures for pin pullers	√	
Track pin puller performance over multiple actuations	√	√
Integrate and use the TUI tether deployer	√	√
Demonstrate use of IMUs for future S3FL projects	√	√
Demonstrate use of OOPIC microcontrollers for future S3FL projects	√	√

Table 2: Project objectives met during ground and flight testing.

3.4 Outreach

Outreach activities sponsored by TSSIT included multiple workshops designed for the elementary to middle school age group. These workshops were a way to encourage students to further pursue their education in the science and engineering fields. By conducting hands-on projects and tours coupled with brief classroom lectures, the students were able to learn and then apply that knowledge to group activities. Workshop topics included rocketry, aerodynamics, blimps, and presentation skills. The team also worked with the Michigan Space Grant Consortium to address groups of home-schooled elementary-aged children looking for weekend science-based activities. Figure 2 shows a sampling of some of the workshop activities conducted by the team.

In addition to activities for elementary and middle school aged groups, TSSIT publicized the project at University events including FestiFall, NorthFest, and AeroFest, where student groups present their projects and spark interest in new students to join. The team's website is linked to the main S3FL website (http://data.engin.umich.edu/s3fl/) where information can be found about all of the projects, both past and present, going on in the lab.

Figure 2: Students experience what 50 mph wind feels like behind the University of Michigan's Aerospace Department's 2'x2' wind tunnel (top left). Classroom instruction occurs prior to the design activities (top right). Each student flies the blimp around the atrium via remote controls built into the system (bottom left). Students build and launch their own model rockets (bottom right).

4.0 Lessons Learned

Throughout the design process, there are often many unexpected issues that arise, from longer than expected lead times on hardware to troublesome software interfaces, and all of these events have value as lessons learned. Team members gain experience from these and are able to take this knowledge with them to future projects that may encounter similar problems. Lessons can be taken from all phases of the design cycle, and S3FL takes care to disseminate them to all lab members.

4.1 Conclusions drawn from testing and experience

Based on the S3FL goal of providing hands-on space systems work for undergraduates, it is important for students to understand the full design cycle, work on hands-on, interdisciplinary projects, and develop a systems engineering mindset.

4.1.1 Understanding of entire end-to-end design cycle

In working on TSSIT, students experienced all phases of a space mission and learned valuable lessons from each step. In order to be accepted to the NASA Reduced Gravity Program, TSSIT was required to submit a technical proposal outlining the project. Project definition began in late August 2005, with refinement continuing through the fall semester. The proposal was submitted in October 2005, and the team learned of its acceptance to the program in December 2005. In the design phase, students faced the challenge of designing all aspects of the system with requirements traceability. As requirements evolved and changed, so did the design. These modifications were tracked via requirements compliance matrices and systems budgets kept by both TSATT and TSSIT. The importance of thorough trade studies was learned, as design decisions required reevaluation and justification when changes were requested. Trade studies were conducted by team members in all subsystems and also at the system level to assess, analyze, and compare prospective performance and cost of different design configurations. The design process was iterative with two design review milestones. To reduce problems during the assembly of the system, it was important that interfaces between subsystems were communicated and kept consistent.

Once the design was approved at the Preliminary Design Review (PDR), the build phase began. One problem the team faced was the availability of facilities in which to fabricate hardware. The Wilson Student Project Center offers the use of equipment such as mills, lathes, and CNC machines, but these resources must be shared by many project teams, and the desired equipment is sometimes not available. Tolerancing also became an issue when designs called for precision beyond the capabilities of the student machinists to fabricate them. The team experienced the culmination of these factors in the original spring cap design machined for the separation mechanism. When the mounts could not be properly aligned to allow for a smooth separation, the mechanism had to be quickly redesigned and machined to alleviate the friction and alignment problems in the system. This late redesign resulted in a separation mechanism that allowed the halves to separate, which the previous design could not accomplish during ground testing. The main lesson learned in the fabrication stage was that student machining is not perfect, and this should be accounted for when planning a design. Starting the machining early allows time for more accurate machining, test fitting, and re-machining if needed to accommodate adjustments to the original design.

TSSIT was composed mostly of aerospace engineers, who did not have expertise with electrical systems, and therefore ran into difficulties when working on this aspect of the project. Fortunately, the team was able to recruit electrical engineers with a better understanding of how to design and construct the electrical system to meet the needs of the team. Due to the limited knowledge of team members on the command and data handling (C&DH) system, which includes having to program microcontrollers, this aspect was also addressed near the end of the design process with the aid of upper classmen and electrical engineering students. The team learned how vital it was for these issues to be worked out as early as possible, because there are always bugs in the system the first time around, and circuit boards may need to be reordered or rewired. It was also necessary to have all processes and troubleshooting procedures documented and available so the flight team members in Houston were able to work out problems that developed during shipment or during an Integrated Systems Test (IST) on location. It was important to have the team familiarized with the whole system and how it functions prior to leaving for flight. Even if they did not work on building a specific aspect of the project, it was crucial that all team members knew what to expect and how the system works when everything is functioning properly, as evidenced by the organized troubleshooting effort that took place when flight problems were encountered.

When the testing phase began, a whole new set of lessons was experienced. As a way to ensure that components perform as expected, individual functional ground tests were conducted. For instance, prior to wiring the pin pullers together so they operated simultaneously, each one was tested by itself, and its actuation times were recorded. As was learned the hard way, it was vital to track documentation and check that the specification sheets being used as reference are up to date. The type of pin pullers used on TSSIT had been redesigned by the manufacturer since their purchase, and the specification sheets online were no longer valid. This led to load testing that exceeded the allowable value for the older pin pullers and necessitated in replacement of one of the pin puller components during ground testing. The overall lesson from the testing phase was the importance of prototyping and testing early to allow time for design modifications and to drive out any unanticipated problems during the design phase.

After individual component testing was completed, systems were integrated. Full ISTs were conducted prior to leaving for flight. Even though the team had time for assembly and testing in Houston, a successful IST was required by Excom in order to receive the “go” for flight. This turned out to be very beneficial to the team, as it was known that everything worked the way it was expected to prior to leaving for Houston. This way, the flight team was not trying to conduct new ground tests outside of the lab where there was limited access to equipment and help from lab members. Once in Houston, the only testing required was another IST to make sure there were no problems encountered from shipment to Houston and onsite assembly. This reduced the stress of the flyers during flight week, and it also allowed for more free time in which the flyers could rehearse flight procedures. In order to practice flight plans, the team developed a color-coded flow chart in a comprehensive decision tree format. This made for easy assessment of the test sequence based on in-flight test performance and contingency actions. The flow chart also allowed for NASA flight crew to understand the testing procedures and to help when needed.

Once the design, build, and testing phases were completed, the team began documenting the results obtained during the flight operations phase. This involved compiling data, performing analysis, and reporting the results to the NASA Reduced Gravity Office and S3FL. All test procedures and lessons learned were documented and made available for future use. From these lessons learned, future teams will be able to avoid similar difficulties experienced in TSSIT’s iterations of the design cycle.

4.1.2 Working on hands-on, real-world projects

TSSIT worked in collaboration with TUI and Lockheed Martin. From this, team members gained experience with real industry practices. Interface Control Documents (ICDs) were generated to facilitate the integration process once hardware was procured from industry, and teleconferencing was an important mode of communication with TUI prior to hardware delivery. Multiple external deadlines with TUI and NASA needed to be met, and the team had to manage vendors’ delivery delays that impacted the project schedule. From the experience of working with external entities, the team learned how these formal interactions take place, such as having a single point of contact to facilitate communications, setting up ICDs to define interfaces, and negotiating deadlines and expectations, all of which are very beneficial experiences for the team members and their future work both in S3FL and in the workplace.

Because the purpose of TSSIT was to test the separation mechanism concept for TSATT, it was imperative that the teams stayed in close contact throughout the entire design process. All members learned the importance of close subsystem communication and regular meetings with the TSATT group to ensure that all TSSIT designs were applicable to TSATT programmatic objectives and that adequate time existed to support design alterations.

Cost and schedule are other real-world aspects the team was required to address throughout the project. Vigilant cost budgeting with built-in margins was vital for the project, so that funds were available for all needed hardware and any emergency, last-minute items that may be needed. Scheduling deadlines imposed by NASA regarding document submission, security information, and flight physicals had to be met alongside the S3FL requirements of design reviews, document reviews, and successful functional ground testing. Occasionally it was a rush to meet the deadlines, requiring team members to put in extra hours to ensure the milestone would be met. These experiences stress the importance of not letting the schedule slip early on in the project.

4.1.3 Developing systems engineering mindset

Part of the mission of S3FL is to help create in undergraduate engineers a systems engineering mindset, which they may not develop in general classroom instruction. Intuition about an overall system is not something that young engineers necessarily have, and by seeing the entire design process and how the project comes together during the final integration and testing phases, students develop a better understanding of space systems engineering.

One key part of systems engineering is ensuring that all aspects of the design are validated and flow down from system requirements. This was experienced during design reviews with Lockheed Martin, in which requirements and design decisions were thoroughly scrutinized. A complete understanding of the system and the rationale behind design decisions are imperative for the team members presenting, and reviews often result in these decisions being revisited to make sure they are the best way to meet requirements. Systems requirements flowdown ties directly into the holding of periodic design reviews that are attended by faculty, Excom, and members of the TSATT team to make sure all design decisions and requirements are in alignment with the TSATT project's needs, including functionality, scaling, and interfacing.

With the turnover of students between semesters and the availability of team members during the summer months prior to flight being limited, many team members were able to experience various roles on the team. From subsystem member to subsystem lead to team lead, students were able to participate on varying levels of commitment and responsibility. This required that many team members be informed about the overall system and be familiar with integration and testing of the final flight unit. A particularly challenging situation arose during the summer prior to flight, when internships and out-of-town commuting realities led to the difficult situation of needing to switch onsite leads every other month. This situation was mitigated with the aid of Excom providing administrative oversight, mentorship, and continuity, and as a positive outcome, more students were given the opportunity to experience a lead role and the demands of a systems engineering position. These students were exposed to more responsibility and were able to shadow the leads preceding them, thus gaining knowledge based on the lessons learned throughout the project. By having the lead mentor the assistant, this followed S3FL's teaching style of "see one, do one, teach one," where the student is able to observe the lead, take a leadership role, and then pass on the experience and knowledge they have gained to the next generation of team leads. Consequently, the development of team members was accelerated, resulting in TSSIT members being able to assume team lead and assistant lead roles for this year's new C-9 projects.

4.2 Application to new projects

Due to the success experienced by TSSIT, many more students were interested in flying on microgravity flights. To meet this demand, S3FL formed three flight teams that all proposed different projects to NASA in the fall of 2006. In December 2006, flight teams were announced, and all three teams were granted flight opportunities. Administrative, project management, and general technical lessons learned for TSSIT have been compiled and are being applied to these new projects. These include secondary objectives of understanding, integrating, and testing of various system components such as the IMUs, OOPIC microcontroller, and tether deployer.

4.2.1 C-9 Reflight

The C-9 Reflight project is a follow-on to TSSIT. During the first day of TSSIT's microgravity flight, one of the pin pullers malfunctioned. While the pin puller was replaced, and the following microgravity tests were successful, the separation of the end masses was not uniform under different types of tip-off conditions. Another issue with the TSSIT microgravity tests was that the data acquisition system responsible for measuring the differences in actuation time of the two pin pullers could not sample at a high enough data rate to capture the actuation of either of the pin pullers. The primary mission objective of the C-9 Reflight team is to design, fabricate, and test the next-generation separation system prototype for TSATT and demonstrate its improvement over the original design. To do this, the C-9 Reflight project will use the lessons learned from TSSIT to develop a refined separation system and procedures to better determine the dynamics of the separation. The clampband model being used for Reflight is shown as a CAD model in Figure 3.

Testing of the satellite end mass system will be conducted in the same way as TSSIT. This will allow for better comparison of the first- and second-generation separation systems. Camcorders oriented along the coordinate axes will be used again to capture qualitative data; however, a fourth camera will be incorporated into the setup to accommodate for drift during free float periods. To quantitatively track the end masses, IMUs, which track six degrees of movement, will be used. The data gathered from flight, both qualitative and quantitative, will be analyzed after the flight to determine the dynamics of the separation system as well as the tether dynamics of the end mass pair. This will be used to characterize and to refine the separation system further if needed.

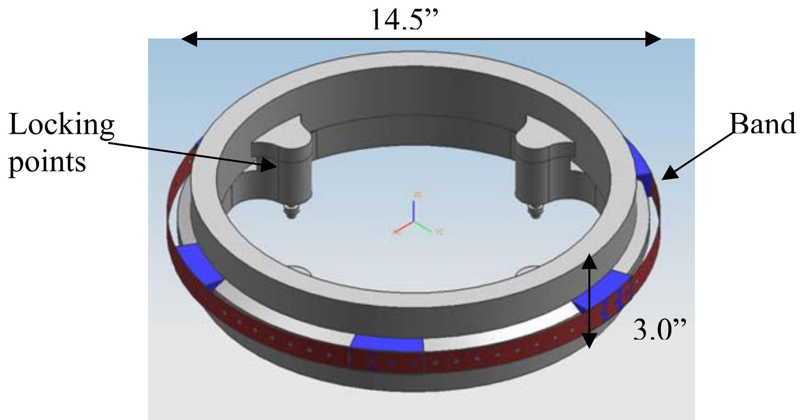

Figure 3: Reflight's clampband-based separation system.

4.2.2 C-9 Nano

A project already in progress at the University of Michigan is known as Nanoparticle Field Extraction Thruster (nanoFET) [8]. The objective is to create nanoparticle electrostatic propulsion by charging and extracting nanoparticles from a liquid reservoir[9]. A main concern is what effect a zero-gravity environment has on a liquid surface being exposed to high electric fields. When a large enough electric field is applied to a liquid, Taylor cones form on the surface of the liquid and hinder the propulsion performance of nanoFET. Since nanoFET is being designed for use on space vehicles, it is desirable to know if sufficient electric fields to extract particles from the liquid can be generated without causing the Taylor cones to form in microgravity.

4.2.3 C-9 DERBI

The Dynamic Extendable/Retractable Boom Investigation (DERBI) project is based on the concept of deployable structural booms for space applications. This project was inspired by TUI's proposal to the NASA Institute of Advanced Concepts (NIAC) for research into Modular Spacecraft with Integrated Structural Electrodynamic Propulsion (ISEP).[7] Many space booms are used as foldable structures for solar arrays or for isolating instrumentation from the spacecraft. However, the zero-gravity shape and dynamics of boom systems are less understood as the structure is deployed. In an attempt to uncover the underlying physical mechanisms of such devices, the DERBI project will design and build an extendable/retractable boom on a reduced scale. The purpose of this project is to test the validity of the entire system in a zero-gravity environment and in particular, the challenges of extending and retracting a boom given an initial rotation. The flight data generated will be used to develop a computer simulation to model the general dynamic properties of the boom structure. The knowledge obtained will be used to improve upon the current boom design and research other deployable structural mechanisms to support projects currently under development within S3FL.

Conclusion

As a way for students to gain hands-on experience building hardware to test space concepts, S3FL has provided a unique opportunity to many students. When discussing the value of the C-9 microgravity experience, it is important to look not only at what was learned from the flight test, but also at the experiences gained by the team and the lessons learned they have been able to pass on to current teams. With the design-build-test cycle in place, students gain experience that may not otherwise be found in the typical classroom curriculum. The building of team skills and the experience of being weightless are invaluable both for future professional work and also as a personal experience.

Acknowledgements

TSSIT would like to thank S3FL for making the opportunity to work on a flight project possible. Thank you to the S3FL Executive Committee members and TSATT members, including Chris Deline, Yang Li, and Selina Pan, and the ME 450 team of Mike Eller, Matthew Carnaghi, Eugene Kheng, and Emily Marks, who were instrumental in the separation mechanism design and fabrication. Special thanks to the S3FL Machining team, especially Justin Weikart, for all of their help over the summer. The authors thank the Michigan Space Grant Consortium and Women in Science and Engineering for their financial support, as well as Tethers Unlimited, Inc., especially Nestor Voronka and Ian Barnes, for the tether deployer and technical advice. Thanks to Lockheed Martin representatives, especially Ed Boesiger, for technical advice throughout the project. Finally, thanks to all the people in the NASA Reduced Gravity Office for the flight opportunity and all of their guidance and help along the way.

Bibliography

[1] Bilén, S.G., Bernal, L.P., Gilchrist, B.E., and Gallimore, A.D., “The Student Space-Systems Fabrication Laboratory: Enhancing Engineering Education Through Student-Run, Real-World Projects,” ASEE-NCS 1999 Spring Conference, Pennsylvania State University Erie-Behrend, Erie, PA, 8-10 April 1999, pp. 68-72.

[2] Liu, T., Deline, C., Ramos, R., Sandoval, S., Smetana, A., Gilchrist, B., Washabaugh, P., and Renno, N., “The Student Space Systems Fabrication Laboratory: An Approach to Space Systems Engineering Education,” ASEE-2006-1917, 113th ASEE Conference, Chicago, IL, 18-21 June 2006.

[3] Reduced Gravity Flight Opportunities Program, http://microgravityuniversity.jsc.nasa.gov/

[4] Bilén, S.G. and Bernal, L.P., “Get Away Special Payload G-093: The VOrtex Ring Transit EXperiment (VORTEX) Flights,” 1999 Shuttle Small Payloads Symposium, Annapolis, MD, 13-15 September 1999, NASA/CP-1999-209476, pp. 129-138.

[5] Millard, L., Myers, B., Shoemaker, D., Woloszyn, M., and Washabaugh, P., “THIRMA: Thermally Induced Refraction in a Micro-gravity Atmosphere,” 2002 Reduced Gravity Flight Opportunities Program Final Report.

[6] Lessack, S., Smetana, A., Woelk, W., and Wind, R., “Tethered Satellite Dynamics at Separation Investigation,” 2006 Reduced Gravity Flight Opportunities Program Final Report, University of Michigan, October 2006.

[7] Carnaghi, M., Eller, M., Kheng, E., and Marks, E., “Tethered Satellite Separation System for TSATT,” ME 450 Final Report, University of Michigan, April 2006.

[8] Liu, T., Keidar, M., Musinski, L., Gallimore, A., and Gilchrist, B., “Theoretical Aspects of Nanoparticle Electric Propulsion,” AIAA-2006-4335, 42nd Joint Propulsion Conference, Sacramento, CA, 9-12 July 2006.

[9] Musinski, L., Liu, T., Gilchrist, B., Gallimore, A., and Keidar, M., "Nanoparticle Electric Propulsion: Experimental Results," AIAA-2006-4803, 42nd Joint Propulsion Conference, Sacramento, CA, 9-12 July 2006.

[10] Voronka, N., Hoyt, R.P., Gilchrist, B. E., and Fuhrhop, K., "*An Architecture of Modular Spacecraft with Integrated Structural Electrodynamic Propulsion (ISEP)*," NIAC 7th Annual Meeting, Tucson, AZ, 18 October 2006.