Three Project-Based Approaches to Spacecraft Design Education

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Abstract - In order to provide a realistic, hands-on educational experience for spacecraft design students, three complimentary project-based spacecraft design activities have been developed. These design programs are similar given that each relies on simplicity, speed, and self-sufficiency. These attributes 1) allow students to understand the full technical design of a spacecraft system, 2) expose students to the full developmental lifecycle, and 3) introduce students to the challenges of managing a team in order to engineer a complete system. The programs differ in their fidelity and comprehensiveness in order to provide a spectrum of approaches from which educators may select based upon their resources.

This paper discusses the educational objectives of these project-based spacecraft design programs. It also reviews the specific design guidelines and strategies for each. Finally, it presents 5 years of results from previous and ongoing projects, and it presents future educational enhancements and spacecraft missions.

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1. INTRODUCTION

Traditional engineering institutions typically focus on the understanding, analysis, and optimization of specific technical disciplines. These schools typically place less emphasis on multidisciplinary synthesis and the design of complex systems. Programs that do extend their programs to these aspects of engineering usually limit their scope to conceptual, paper-based designs or to loosely traceable artifact fabrication.

Introducing students to more realistic design activities has a suite of advantages. These include exposure to technical breadth, involvement in all development phases, accountability to a customer, first-hand accommodation of manufacturing and operability considerations, working within a team, and a variety of other real-world experiences. Of course, implementing such an experience can require vast resources. Particular challenges include money, time, facilities, equipment, and experience.

In response to these issues, the author has been involved in the creation and implementation of several project-based spacecraft design programs at Stanford University, Santa Clara University, and the Space Engineering School at the Space Physics Institute in Sweden. Each of these programs has been integrated into a comprehensive academic program that also includes detailed classroom instruction and technology development.

2. EDUCATIONAL OBJECTIVES AND STRATEGIES

To provide a more realistic, comprehensive, and valuable educational experience for the spacecraft design field, a project-based strategy has been adopted. When integrated with a supporting and more traditional curriculum, this approach provides a powerful learning experience that is routinely characterized as the most valuable and unique element in the participating educational programs.

The educational objectives for each of the spacecraft design projects described in this paper include exposure to each of the following experiences:

- **Multidisciplinary System Design:** By nature, spacecraft systems typically require a wide range of technologies and functions in order to sufficiently support their missions. In synthesizing a design by drawing from a variety of disciplines, students directly experience the interrelated functional effects that are typical of complex systems.
- **Complete Development Lifecycle:** Students follow a design from conception through detailed design, fabrication, integration, test, launch, and operation. This not only allows them to experience each phase, but it also permits them to realize the benefits of considering future lifecycle phases early in the development cycle.

- **Systems Engineering and Concurrent Design:** The principles and methodologies associated with the fields of systems engineering and concurrent design are naturally motivated given the comprehensive technical and lifecycle breadth of the projects. Students are able to learn first hand the importance of sacrificing what may seem as optimal solutions at the subsystem level in order to optimize the overall system.
- **Team-Based Activity:** Working with other students in order to achieve a goal beyond the capability of an individual is often a new experience to students but which is one that is typical in industry. This feature requires students to collaborate, to compromise, and to depend on the ability of other design team members.
- **Project Management:** All three projects rely on students to manage themselves in order to identify and organize required tasks and to apply personnel, equipment, time, and monetary resources to these tasks in order to complete the project.
- **Customer-Driven Development:** Customer driven missions ensure a continuing accountability to an external source of requirements. This is a realistic situation that at times can be frustratingly ambiguous, shifting, and difficult to achieve.

To provide a valuable and yet achievable experience, a number of principles have been adopted for the project-based approaches.

- **Simplicity:** Simplicity allows all involved students to understand the technical functionality of the entire system. It also limits the scope of the projects in order to support timely completion.
- **Rapid Development:** A short development cycle ensures that the project can be completed within the average timeframe of student involvement. This allows students to be involved from conception through detailed design, fabrication, integration, test, launch, and operation. It also reduces problems associated with team continuity over time.
- **Early Prototyping:** Early prototyping is valuable for exploring the design problem as well as for providing proof of concept demonstrations. Within the student environment, it also allows educators to quickly assess the technical and managerial capabilities of the team.
- **Formal Methods:** Formal systems engineering and concurrent design methodologies serve several purposes. First, they teach students how to use valuable tools that support these philosophies. Second, they provide a useful structure through which to control the project. Third, their rational focus improves the design process as well as the form of the final artifact.
- **Low-Cost:** Designs that can be implemented within modest budgets are essential given the financial limitations of most educational programs. To do this, projects must rely on re-engineering commercial off-the-shelf (COTS) components, on developing nontraditional functional approaches, and on educational discounts and donations.
- **Motivational Impetus:** Several factors provide motivation for these projects. Each has a "bragging rights" reputation derived from extensive but worthwhile effort. All have a distinguishing entertainment or "coolness" factor. Finally, excellent performance leads to selection for follow-on academic and/or industrial opportunities.

These principles are, of course, relative to the attributes of the educational environment. For example, the available time, money, and experience of graduate programs specializing in spacecraft design are typically more than that of undergraduate curricula that are simply offering a single technical elective in the same field.

3. A SPECTRUM OF APPROACHES

The educational objectives and strategies reviewed in the previous section have been incorporated into three distinct hands-on spacecraft design projects. These three approaches vary in scope, comprehensiveness, and fidelity. Similarly, they range in the level of resources and experience required for their execution.

The Kiwi satellite project was designed as the project/laboratory component of an introductory satellite system design course. It involves the development of a mock satellite by a very small team of students for a complete cost on the order of tens of dollars. The ParaSat program was designed for an undergraduate senior design project team with a budget on the order a few thousand dollars. It involves the development of a flight quality system with many but not necessarily all typical spacecraft subsystems. The SQUIRT program was designed as the primary educational component of a graduate satellite

Table 1 – *A Comparison of Spacecraft Design Projects*

	Kiwi	**ParaSat**	**SQUIRT**
Satellite Fidelity	Mock	Flight	Flight
Mission Life	Minutes	Hours – Weeks	Months - Year
Mission Objectives	Entertain and educate	Test component	Science and technology
Subsystems Included	All	Most	All
# Students	2–4	5–10	25–100
Student Grade	Grad and undergrad	Undergrad	Grad and undergrad
Student Experience w/ Satellites	None	None	Satellite design courses
Team Effort	50–200 hrs	1000–4000 hrs	8000–12,000 hrs
Material Cost	\$10 – \$100	\$1,000 – \$10,000	\$25,000 – \$100,000
Time (month)	2–3	9–18	12–48
Facility	Home or office	Garage or simple laboratory	Simple or extensive laboratory

design program. It involves the development of a completely functional flight quality system. It involves dozens of students, one or more years of time, and up to $100,000.

Table 1 compares each project on the basis of typical spacecraft attributes and required resources. As can be seen, these three projects constitute a full spectrum of choices for educators based upon their objectives and resources.

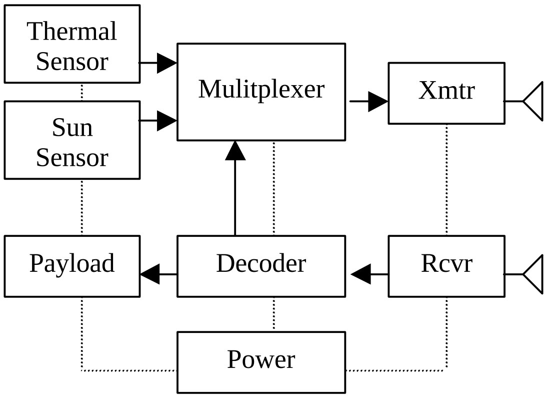
4. THE KIWI SATELLITE PROJECT

The Kiwi Satellite Project was initiated in 1994 with the goal of introducing engineering students to basic hands-on aspects of subsystem functionality, end-to-end lifecycle development processes, and project/team management [1]. The project was designed as the project/laboratory component of an introductory satellite design course suitable for both undergraduate and graduate students. Figure 1 shows aspects of a typical Kiwi satellite project.

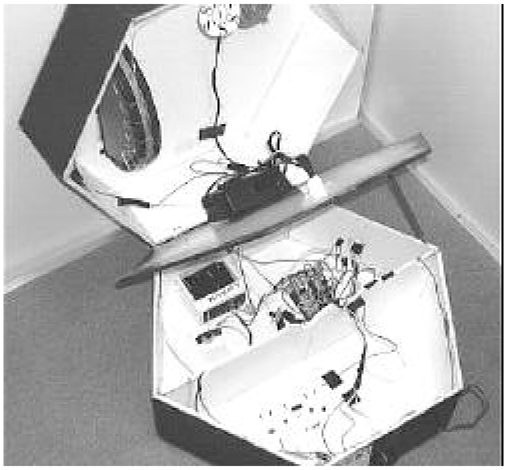
The project consists of teams of 2–4 students that conceptualize, design, fabricate, launch, and operate non-space capable "satellites". These electromechanical objects function like real spacecraft in that they interact with users and are remotely controlled by operators. Each satellite qualitatively meets many system requirements common to real spacecraft such as withstanding simulated launch loads, communicating remotely, sensing on-board conditions, and actuating mechanisms. Each standard satellite function is represented in the project such that students are truly exposed to the wide scope of technologies found in real spacecraft. Furthermore, the student teams utilize industry standard design methodologies and project management techniques in order to ensure requirement satisfaction, system integration, and project success. The functional similarity between the resulting projects and real spacecraft has led to the nickname "Kiwi satellites" because they are "built to fly, but never will."

Figure 1a displays a typical block diagram for a simple Kiwi satellite. A multiplexer chooses among two sensors for telemetry transmission. Switching is performed via a received command. Commands are also used to initiate payload operations. The exact system layout as well as component designs are all based upon trade-offs performed by the student teams. For instance, communications techniques have ranged from basic radio communication to infrared emitter/detector pairs to audio "clapper" circuits. Payloads are required to "entertain" the audience that gathers at the public demonstrations of the satellites; payloads have included tape recorders playing music, flashing light shows, deployable robotic appendages, and ejected rovers.

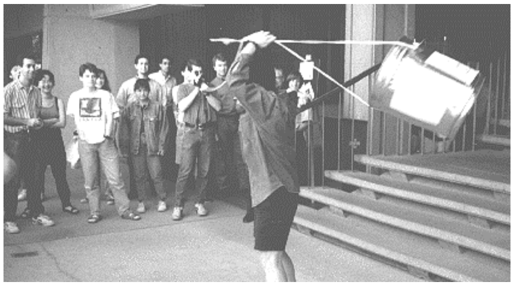
A particular benefit of the course is its ability to prepare students for the activities they encounter in more complex systems engineering projects. Based upon experiences in Stanford University's Space System Development Laboratory's (SSDL) research activities, graduates of the Kiwi project are far more attuned to system level concerns, cognizant of integration issues, versed in a range of subsystems and lifecycle phases, and realistic in gauging their own abilities and schedules. In addition, they understand the need and uses of documentation and develop a variety of novel methods for modifying low cost commercial components for their designs. Finally, the hands-on nature of the course mandates the development of bench engineering skills (some students have never soldered a circuit or even used a spray paint can), lab and equipment discipline, and experience with searching for and acquiring parts.



(a) Block Diagram of a Typical Kiwi Satellite



(b) Physical View of a Typical Kiwi Satellite



(c) Axial Loading During a Simulated Kiwi "Launch"

Figure 1. *The Kiwi Satellite Project*

Success with the Kiwi satellite project has ingrained it as an essential element in Stanford's introductory graduate-level spacecraft design course. Furthermore, at Sweden's Space Engineering School, this project was proclaimed to be the "crown jewel" of the 3 year satellite technology curriculum. Santa Clara University is planning to incorporate the Kiwi project into its undergraduate curriculum in the 1999-2000 academic year.

5. THE PARASAT SPACE FLIGHT PROGRAM

The ParaSat space flight program was initiated in 1997 with the goal of producing student managed and engineered spacecraft that contribute to the educational experience while also providing a platform capable of supporting very inexpensive albeit risky space experiments [2]. It was specifically developed in order to guide the scope and strategies of university satellite programs with limited resources and capabilities. Typical limitations include one or more of the following: money, time, facilities, equipment, and expertise.

The general ParaSat configuration guideline is to be on the order of 1 ft^3 and to weigh less than 15 kg. Simple, short-duration missions and the potential for acquiring resources, such as power, from host vehicles often allow the spacecraft to provide only a subset of the functionality typically offered by conventional satellites. This scope is appropriate for a small interdisciplinary team of senior level undergraduate engineers for a year-long design project; little to no space-related coursework is required for these students.

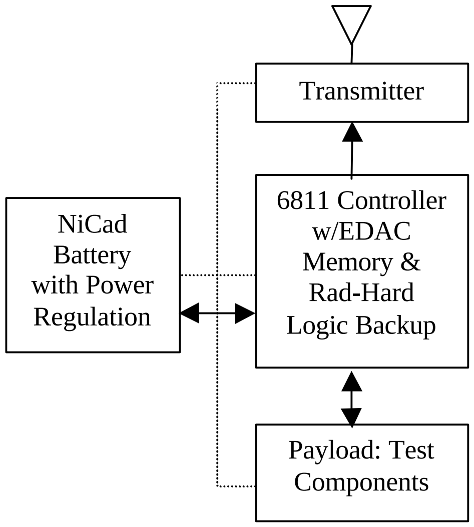
Students assist with the fundraising in order to conduct these projects. These activities typically involve writing proposals and giving presentations in order to earn cash awards/donations from the host university, local corporations, and professional societies; each of these sources typically provides worthy projects with funds on the order of hundreds to thousands of dollars. Students also arrange in-kind component donations for material and electronics. Advisor assistance is used to broker deals involving possible payload customers. Free or very low-cost launches are targeted through the following strategies: permanent attachment to a rocket upper stage, inclusion as an isolated subsystem in a more complex satellite, and existence as an end-mass for a gravity-gradient boom or tether. Finally, in order to further limit cash requirements, students re-engineer commercial terrestrial equipment never intended for space flight.

The name "ParaSat" was derived from two particular features of the program. First, because a ParaSat-class spacecraft does not need to provide all subsystem functions provided by conventional spacecraft, the "para" prefix was used to denote a mechanism that "closely resembled" a typical satellite. Second, because a ParaSat-class vehicle may be permanently attached to another vehicle and may even consume some of its resources, the humorous resemblance of "ParaSat" to "parasite" was considered appropriate.

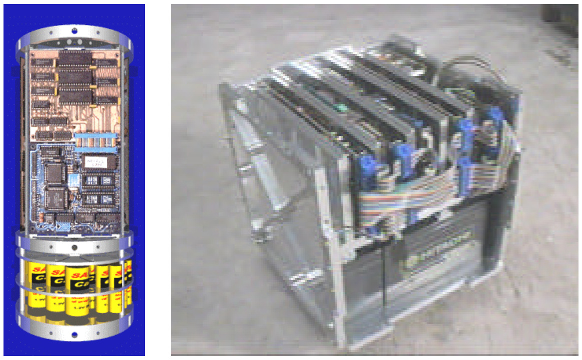
Several ParaSat class missions have already been accomplished or are in development. These include two 15 kg microspacecraft, several 0.5 kg picosatellites, and a 2 kg subsatellite being developed in conjunction with a SQUIRT mission.

The Barnacle Microspacecraft

Barnacle, the first ParaSat spacecraft, is the first microsatellite built by Santa Clara University [3]. Its missions include characterizing experimental sensors and validating the space operation of a new low cost spacecraft computer. This project was completed in one year, involved seven senior undergraduate engineering students, and required a cash budget of less than $5,000. The Barnacle project set an impressive precedent as being the first undergraduate managed and engineered satellite completed in less than 1 year; it also laid the foundation for the Santa Clara Remote Extreme Environment Mechanisms (SCREEM) laboratory.



(a) System Block Diagram



(b) Sounding Rocket Configuration

(c) Orbital Flight Configuration

Figure 2. *The Barnacle Microspacecraft*

Pictured in Figure 2, Barnacle's processor subsystem consists of an experimental Motorola 68HC11 microprocessor, an eight channel data acquisition board, 16 Kb of ROM, 48 Kb of RAM, and backup digital spacecraft control circuit. The communications subsystem is composed of a modified commercial transceiver and software based 1200 baud data packetization. Barnacle is manifested for launch in April 1999 on an experimental sounding rocket as part of the CATS (Cheap Access To Space) prize competition. For this flight, components have been packaged in a 6 in. diameter tube; power will be supplied by the launch vehicle.

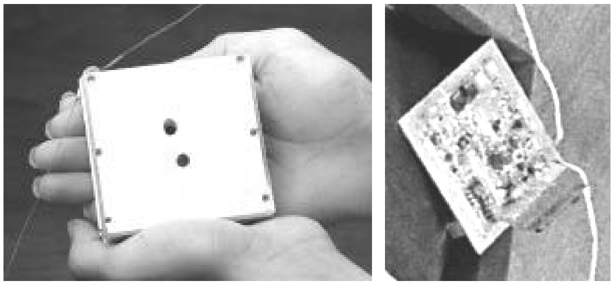
For subsequent orbital flights, an alternate flight configuration has been developed. This consists of a 9 in. cube machined aluminum structure that houses components in an internal tray system and that includes a single lithium ion battery that provides five and 12 volt regulated power to components. This platform is designed to be permanently affixed to a launch vehicle upper stage and to operate for a lifetime of a few weeks.

The Artemis Picosatellites

The Artemis project consists of an all-female team of seven Santa Clara University seniors. The Artemis group is exploring the capabilities and limitations of picosatellite sized space vehicles [4]. Several of these picosatellites will be ejected by Stanford's Opal microsatellite (discussed in Section 6), which has been manifested for launch in September 1999. The all-female nature of the team has served as an extra source of motivation for the group. In addition, it has also allowed the team to publicize opportunities for women in the fields of science, technology, and engineering. It is worth noting that the make-up of the team evolved naturally and was not motivated by any special program for underrepresented groups.

The Artemis pico-satellites have several missions. First, the team will be attempting to enable as much conventional spacecraft functionality as possible within the challenging limitations of volume, mass, and power. Second, the space operation of a micro-electromechanical system (MEMS) component will be evaluated; the evaluation of such devices is crucial to enabling further miniaturization of spacecraft. Third, a very simple but compelling science experiment that capitalizes on a distributed sensing architecture will be attempted; currently, measuring the spatial amplitude variation of lightning-induced very low frequency (VLF) waves is being explored for this experiment.

Figure 3 displays the first functional picosatellite prototype as well as the mothership-daughtership sensing architecture for the targeted science experiment. The range of technical specifications for the picosatellites include the following: a 3 × 3 × 1 inch machined aluminum structure (double-sized structures are also being developed), processors ranging from BASIC Stamps to 68HC11s, sun and Earth sensing, no or passive stabilization, commercial batteries and solar cells, passive thermal control, and amateur radio communications.



(a) Aluminum housing *(b) Electronics*

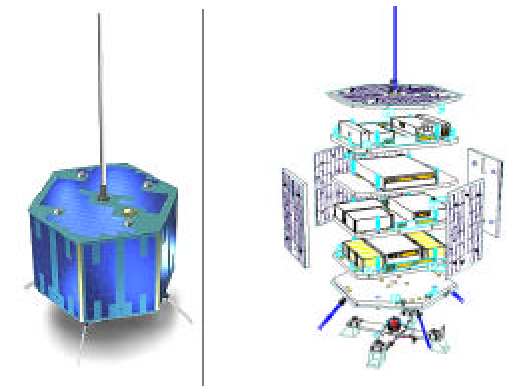
Figure 3. *The Artemis Picosatellites*

6. THE SQUIRT MICRO-SATELLITE PROGRAM

Initiated in 1994, the ultimate goal of the SQUIRT program is to design, fabricate, integrate, and test simple but complete spacecraft capable of supporting state-of-the-art technology research payloads within a 1 year developmental schedule [5]. Educationally, participation on a SQUIRT design team exposes graduate engineering students to project management, conceptual design, requirements formulation, subsystem analysis, detailed design, fabrication, integration, test, launch, and operations. In addition, the SQUIRT vehicles serve as a generic space based platform for the variety of low power, volume, and mass experiments currently under development by the SSDL and its affiliates. The ultimate goal of yearly design cycles will permit rapid access for state-of-the-art space research and unique opportunities for low cost payloads.

Current design guidelines for such vehicles include the following: a modular hexagonal bus configuration as shown in Figure 4; a 12 in. high by 18 in. diameter physical envelope; a 25 lb mass target for the bus; the use of amateur satellite communication channels; and reliance on modified nonspace-rated COTS products. Low mass, power, and volume payloads are selected so that their requirements are compatible with the capabilities of satellites under such constraints. This scope of project requires large interdisciplinary design teams typically consisting of 10–20 active students at any one time. These students participate in the projects for course credit, as part of the dissertation work, and/or as interested volunteers. Student commitment levels range from a few hours per week for a single academic quarter to tens of hours per week for several years.

Through heavy reliance on donations of equipment, facilities, and consulting, cash budgets for SQUIRT vehicles are generally targeted to be $50,000. This level of funding typically necessitates formal collaborations with external customers interested in flying low-cost albeit risky space experiments. At Stanford's SSDL, these collaborations are often integrated with funded dissertation work being conducted by doctoral students within the laboratory. Several SQUIRT-class missions have already been accomplished or are in development.



(a) Assembled View *(b) Exploded View*

Figure 4. *The Typical SQUIRT Configuration*

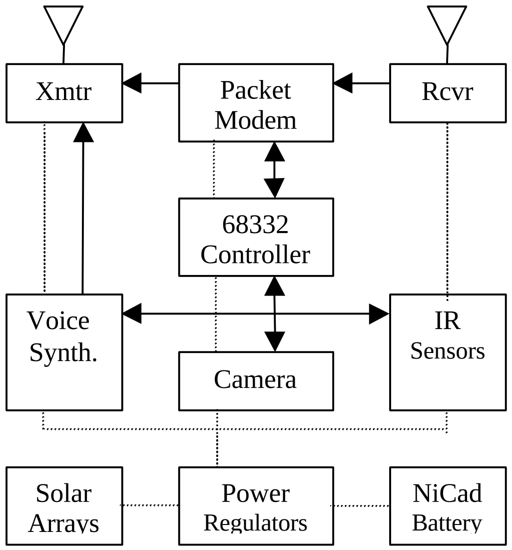
The Sapphire Microsatellite

Sapphire is the first microsatellite developed by Stanford University [6]. Its primary mission is to characterize a set of micromachined infrared sensors developed by Stanford University and the NASA Jet Propulsion Laboratory.

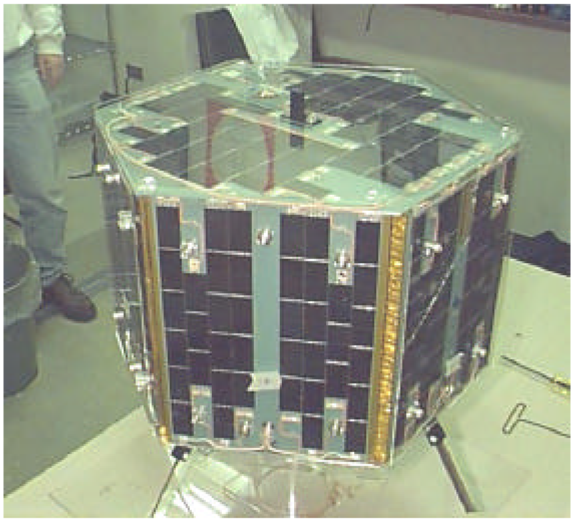
Additional missions include several autonomous operations demonstrations in support of graduate student research as well as providing educational services such as photography and voice broadcasting. Now complete, Sapphire required 4 years, 75 students, and $35,000 to develop. The Sapphire project has been instrumental in establishing Stanford's spacecraft design program; in addition, the basic design parameters have been adopted for use in future SQUIRT microspacecraft.

Pictured in Figure 5, Sapphire weighs 40 lbs and is housed in an 11 in. tall, 18 in. diameter, modular, hexagonal, aluminum honeycomb structure. The power subsystem includes a single 10 cell nickel cadmium (NiCad) battery, 5 and 12 volt regulators, and 8 gallium arsenide (GaAs) solar panels capable of generating 16 Watts of peak power. The communications subsystem is composed of an amateur radio transmitter and receiver, a terminal node controller (packet modem), and a multiplexer to permit either 1200 baud AFSK data or FM voice transmissions. The processor subsystem consists of an MC68332 microprocessor, an interface board, radiation hardened ROM memory, and 512 KB of RAM.

Subsystem components are mounted to one of four trays that are vertically stacked. Exterior solar panels attach to the internal trays. Attitude is passively controlled by the use of permanent magnets, hysteresis rods, and coated transmit antennae that generate a solar pressure-induced spin. Earth sensors provide attitude information. Passive thermal control is maintained through the vehicle's spin, insulation, coatings, and conductive materials.



(a) Sapphire System Block Diagram



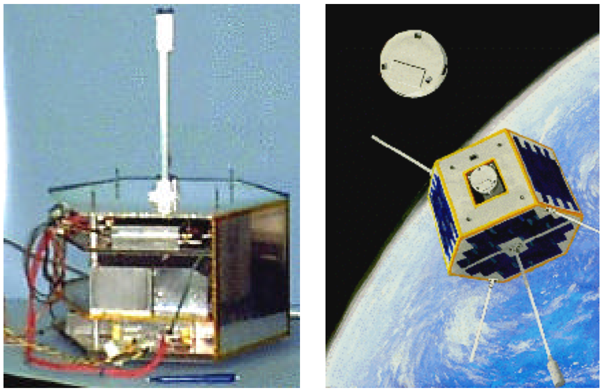
(b) Flight Vehicle Ready for Launch

Figure 5. *The Sapphire Microsatellite*

Sapphire's multi-user bulletin board system permits control of sensor recording, camera operation, voice transmissions, and file downloads. Commands can be executed immediately upon reception by the vehicle or they may be stored for future execution at a designated time. A simple production rule system enables on-board anomaly detection and response as well as state-based vehicle control.

The Opal Microsatellite

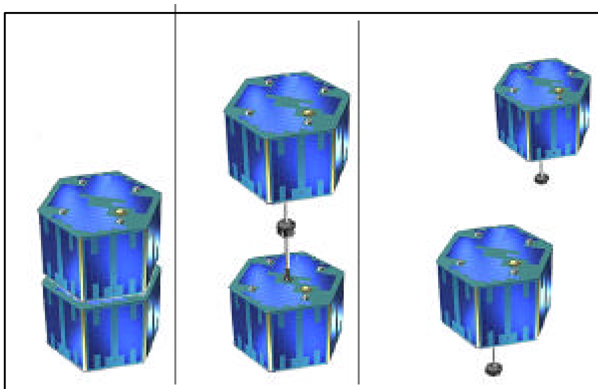
Opal is Stanford's second microsatellite [7]. Its primary missions are to validate technologies for launching and operating small picosatellites as well as to characterize a suite of commercial sensors. Now in its third year of development, OPAL has involved 50 students and has required $25,000 to purchase parts; it is scheduled for launch in September 1999.



(a) Opal Flight Vehicle During Component Test

(b) Artist's Conception of Picosatellite Launch [Tillier]

***Figure 6** – The Opal Microsatellite*



(a) Stacked Operations

(b) Boom Operations

(c) Separated Operations

***Figure 7.** The Two-satellite Emerald Mission with ParaSat Boom End-Weights*

OPAL, depicted in Figure 6, weighs 32 lbs and is housed in an 9 in. tall, 18 in. diameter, modular, hexagonal, aluminum structure. The power subsystem includes a single 10 cell NiCad battery, 5 and 8 volt regulators, and seven GaAs solar panels. The communications subsystem is composed of an amateur radio transmitter and receiver, a terminal node controller (packet modem); a data rate of 9600 baud is supported. The processor subsystem consists of an MC68332 microprocessor, two data acquisition boards, radiation hardened ROM memory, and 1 MB of RAM.

Subsystem components are mounted to one of three trays that are vertically stacked. Exterior solar panels attach to the internal trays. The spacecraft is permitted to tumble. Passive thermal control is maintained through insulation, coatings, and conductive materials. OPAL's software permits control of sensor recording and picosatellite launches.

The Emerald Microsatellites

Emerald is a new, two microsatellite mission for validating spacecraft formation flying technologies [8]. Emerald is a joint effort by Stanford University and Santa Clara University and is funded as part of the AFOSR/DARPA TechSat 21 University Nanosatellite Program.

The two Emerald mission spacecraft will demonstrate several critical technologies for future formation flying missions. These include the following: 1) coarse, global positioning system (GPS) based relative positioning through the use of modified Mitel 12-channel receivers, 2) short range inter-satellite communication of formation control data using modified 9600 baud wireless modems, and 3) coarse position control using microthrusters being developed at Stanford in addition to passive devices such as drag panels and tethers. Using a building block experimental strategy, the research payloads first will be characterized in isolation; they will then be coordinated in order to permit simple demonstrations of primary formation flying control functions such as relative position determination and position control. Figure 7 depicts the evolving experimental configuration in which calibration occurs while the spacecraft are attached, positioning experiments begin with the vehicles constrained by a tether, and finally, experimentation is performed with physically separate vehicles.

The Emerald mission will be the centerpiece of the Stanford and Santa Clara spacecraft design education programs for the years 1999 and 2000. More than 75 graduate and undergraduate are expected to take part in this project; six graduate students are currently planning on participating as principle investigators as part of their dissertation work. In addition to validating basic formation flying capabilities, Emerald will also expand and improve upon the low-cost satellite design, fabrication, and operation techniques that have been pioneered in the university and amateur satellite communities. These techniques represent an important step toward achieving low-cost, rapidly developed spacecraft for multisatellite fleets.

7. CONCLUSIONS

The Kiwi satellite project, the ParaSat space flight program, and the SQUIRT microsatellite program provide a spectrum of project-based approaches for teaching the essential elements of spacecraft design. These provide a range of choices for educators given their objectives and resources.

Each of these hands-on design programs provide essential real-world experiences: 1) exposure to the technical breadth typically found in a complex system, 2) participation in all phases of a developmental lifecycle, and 3) introduction to management and systems engineering tasks within a team environment. In the past 4 years, more than 200 students have participated in one or more of these educational projects. The data compiled from more than two dozen Kiwi projects, two ParaSat projects, and three SQUIRT missions indicate that these experiences greatly enhance standard academic approaches to spacecraft design education. This is evidenced by student testimony concerning the value of the projects, industry demand for students with these experiences, and the observed improvement in productivity of these students once they progress to more advanced research activities.

Several future extensions to these educational programs are currently in development. First, each is being exported to other US and international schools in an effort to strengthen spacecraft design education throughout the world. Second, collaborative multiuniversity projects are being investigated as a way to integrate an additional educational dimension. Finally, a tighter integration of research and education is sought in which ParaSat and SQUIRT veterans join subsequent design teams as principal investigators for dissertation level research.

Together, exposure to satellite technologies, involvement in design team activity, first hand experience with systems engineering techniques, and accessibility of space system research testbeds will serve to improve the capability of a new generation of space system engineers.

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REFERENCES

[1] Christopher A. Kitts, "Spacecraft Design Education and the Kiwi Satellite Project," *AIAA Technical Paper Number 95-3754*.

[2] Christopher A. Kitts and Jeffrey M. Ota, “The ParaSat Space Flight Program,” pending publication in *Proceedings of the International Astronautical Federation Specialist Symposium: Novel Concepts for Smaller, Faster & Better Space Missions, Los Angeles, CA*, April 1999.

[3] Sean Boyle, Pascal Stang, and Nick Woods, "Smaller than Small, Faster than Fast, Cheaper than Cheap: The Barnacle Satellite Project," In *Proceedings of the 12th Annual AIAA/USU Conference on Small Satellites*, September 1998.

[4] Adelia Valdez, Maureen Breiling, Dina Hadi, Corina Hu, Theresa Khulman, Shannon Lyons, and Amy Slaughterbeck, Christopher Kitts, and Jeffrey Ota, “The Artemis Project: Pico-satellites and the Feasibility of Faster, Better, Cheaper,” pending publication in the *Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, CO*, March 1999.

[5] Christopher A. Kitts and Robert J. Twiggs, "The Satellite Quick Research Testbed (SQUIRT) Program," In *Proceedings of the 8th Annual AIAA/USU Conference on Small Satellites, Logan, Utah*, August 1994.

[6] R. Twiggs and M. Swartwout, "SAPPHIRE - Stanford's First Amateur Satellite", In *Proceedings of the 1998 AMSAT-NA Symposium, Vicksberg, MI*, October 1998.

[7] Brian Engberg, Jeff Ota, and Jason Suchman, “The OPAL Satellite Project: Continuing the Next Generation Small Satellite Development,” In *Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites*, September 1995.

[8] Christopher A. Kitts, Robert J. Twiggs, Jonathon How, Freddy Pranajaya, and Bryan Palmintier, “Emerald: A Low-Cost Mission for Validating Formation Flying Technologies,” pending publication in the *Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, CO*, March 1999.

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