DESIGN PROGRESS IN THE SATELLITE QUICK RESEARCH TESTBED (SQUIRT) PROGRAM

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Abstract

Stanford University's Satellite Systems Development Laboratory (SSDL) is achieving positive results in its yearly educational program known as the Satellite Quick Research Testbed (SQUIRT). This project's goal is to produce student engineered microspacecraft capable of servicing state-of-the-art research payloads. SQUIRT spacecraft are about 25 pounds, 18 inches in diameter, nine inches tall, and have a cash budget for parts of approximately $50,000. After 18 months of work, the first SQUIRT design team is in the final assembly and test stage of the Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE) satellite. This microspacecraft will be used to space characterize experimental infrared sensors as well as to perform digital photography and broadcast voice synthesized messages. A second SQUIRT team has initiated the detailed design of the Orbiting Picosatellite Automated Launcher (OPAL) satellite. This microspacecraft will study the feasibility of repeatedly deploying hockey puck sized science craft for research purposes. In addition, several commercial off-the-shelf (COTS) sensors are being flown in order to assess their performance in the space environment. This paper discusses developmental efforts within the SQUIRT program, the design progress of the current SQUIRT vehicles, and future payload concepts and program initiatives.

The SQUIRT Program

Based on a vocal industry demand for realistic education in space systems engineering, the SSDL created the SQUIRT microsatellite program. The goal of this yearly program is to produce student engineered microspacecraft capable of supporting research payloads.

Educationally, the SQUIRT program exposes graduate engineering students to satellite design by providing hands-on technical and managerial experience in the following areas: conceptual design, requirements formulation, subsystem analysis, detailed design, fabrication, integration, test, launch, and operations. With respect to research, 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. Yearly cycles permit rapid access for state-of-the-art space research and unique opportunities for low cost payload iteration.[1]

Philosophically, SQUIRT satellites introduce students to the tenants of smaller, better, faster satellite design. The physical size of SQUIRT vehicles permits low cost secondary launches and contributes to limiting the project's scope. SQUIRT missions push the limits of cost, strip systems to their bare essentials, and provide a platform compatible with a variety of launchers, orbits, and payloads. The one year developmental goal allows students to witness the entire satellite design lifecycle, provides rapid access to space, and focuses efforts towards incremental and iterative technical upgrades.[2]

These educational, research, and philosophical objectives are pursued at the price of increased risk. Design work is completely managed and executed by students; many have little or no hands-on or systems experience. On-board component redundancy is virtually non-existent. Most components are not space rated and are modified based upon incomplete specifications and schematics. Simulation and testing capability is limited and still under development. These drawbacks are mitigated through a high level of integration among the design team, weekly progress reviews, heavy mentoring, direct contact with the COTS

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component engineers, and quarterly design reviews by external consultants and industry engineers.[2]

SQUIRT Spacecraft Missions and Design

To limit the scope of the program and to provide direction in the yearly academic setting, the following SQUIRT design guidelines are stressed: a modular hexagonal bus configuration; a nine inch high by 18 inch diameter physical envelope; a 25 pound mass target for the bus; the use of amateur satellite communication channels; and reliance on modified non-space-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.

For launch, secondary payload slots on conventional launch vehicles will be sought. To date, several such opportunities have been offered to the SQUIRT program, but all have been turned down due to scheduling requirements. Primary spacecraft operations will be performed in the SSDL's amateur satellite ground station. This station is now functional, and students routinely contact operational spacecraft as well as the SAPPHIRE spacecraft in the SSDL assembly laboratory.

The SAPPHIRE Missions

The research mission of the SAPPHIRE microspacecraft is to characterize the space performance of experimental IR sensors. These sensors are non-cryogenic, micromachined, tunneling transducer based components developed by Stanford Professor Tom Kenny and NASA's Jet Propulsion Laboratory (JPL). Figure 1 shows one of the two sensor boards that will be flown on SAPPHIRE. The 28 pin integrated circuit chip in the center of the board houses two of the IR sensors along with their processing electronics. The remainder of the circuit board provides power conditioning for the sensors. These boards are mounted perpendicular to the spacecraft's spin axis. As the Earth moves across the field of view of the sensors, their output response will be recorded and downlinked in order to assess their performance.

SAPPHIRE's educational missions include photography, voice synthesized radio broadcasting, and the evaluation of several design research projects. Space based photography will be achieved with a modified Logitech Fotoman digital camera. A modified RC Systems V8600 voice synthesizer board will convert stored text messages to voice signals for subsequent FM broadcasts. A novel satellite separation system will employ a shape memory alloy Frangibolt as its release mechanism. And finally, an experimental post-processing algorithm will use solar panel current telemetry in order to determine the spacecraft's sun angle.

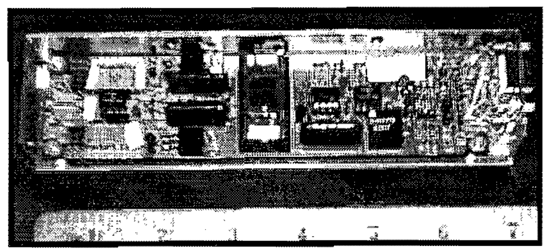

***Figure 1** - SAPPHIRE IR Sensor*

The OPAL Missions

The primary research mission of the OPAL spacecraft is to determine the feasibility of ejecting and communicating with "picosatellite" science craft. As an operational prototype for a proposed JPL mission, the OPAL spacecraft will carry several hockey puck sized science craft, as displayed in Figure 2. These craft will be loaded into an ejection mechanism, spun to a one rotation per second angular speed, linearly accelerated to a one foot per second speed relative to the spacecraft, and deployed. The picosatellites will survive for approximately one hour during which time they will collect sensor data and transmit it to the OPAL spacecraft for subsequent transmission to the ground. This information and relevant telemetry data will be used to assess the repeatability and precision of the launch system.

The secondary OPAL research mission is to characterize the space performance of a variety of COTS sensors. An Applied Physics Systems high precision three axis magnetometer will provide the Stanford Gravity Probe-B spacecraft program with flight data so that it may more effectively use the same sensor on their satellite. JPL will utilize data from an Analog Devices capacitance based accelerometer, a Geophone inductance based accelerometer, an AMP strain gauge, and a PCB piezoelectric sensor. These sensors will measure ambient free flight conditions as well as perturbed conditions resulting from the activation of the picosatellite deployment motors.

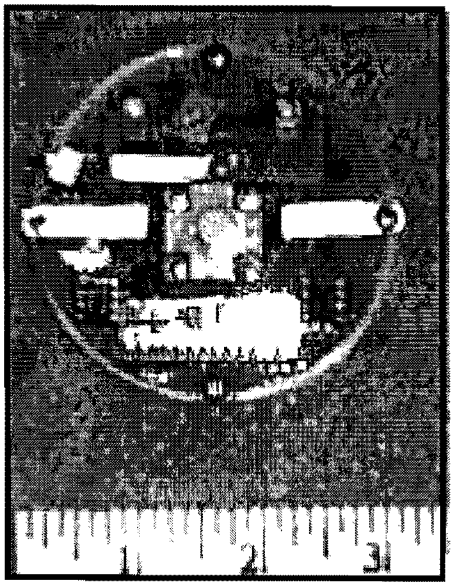

Figure 2 *- OPAL Picosatellite*

Future SQUIRT Missions

In addition to developing the first two SQUIRT spacecraft, the SSDL is actively investigating future payload possibilities. Studies surrounding the flight testing of miniaturized arc jet thrusters have been undertaken with Professor Mark Cappelli of Stanford University's Mechanical Engineering Department. A formation flying mission involving the use of differential GPS and several SQUIRT microspacecraft is currently being outlined with the assistance of Professor Jonathon How of Stanford's GPS and Aerospace Robotics Laboratories.

An inflatable structure experiment has progressed through the conceptualization phase due to partnerships with L'Garde Inc. and the NASA Ames Research Center. An autonomous fault detection and resolution testbed capable of experimental fault injection is currently being planned with the Ames Computational Sciences Division. Finally, a variety of additional micro-electromechanical systems experiments are being planned with Professor Kenny and JPL.

The "Generic" SQUIRT Design

The mechanical design of the current SQUIRT satellites consists of a series of modular aluminum honeycomb trays that are stacked and bolted together as displayed in Figure 3. Component wiring runs along the side of the stack. Eight exterior panels are attached to the exterior of this central structure in order to form a hexagon.

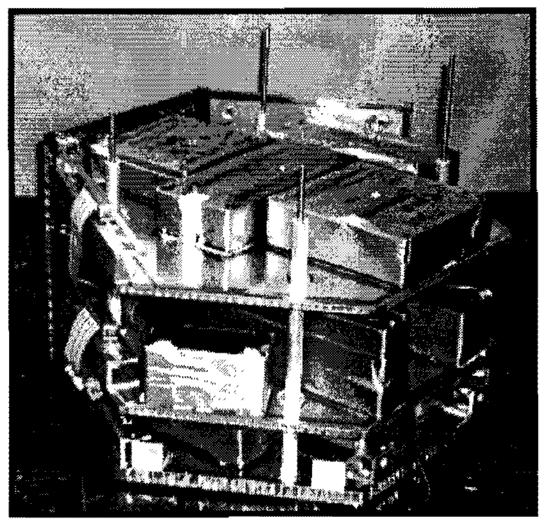

Figure 3 *- The OPAL Test Structure*

Over eight watts of average power is generated with solar cells on each of the eight exterior panels. The SAPPHIRE test solar panel is shown in Figure 4. A single ten cell battery is used to store power. Regulators are used to provide five and twelve volt power buses as well as grounds; an unregulated twelve volt bus and ground is also included.

Attitude determination on the current SQUIRT vehicles is limited to simple photosensitive triggering, post-processed solar panel current telemetry, and the use of payload data. SAPPHIRE's attitude control consists of permanent magnets for alignment with the Earth's magnetic field and radiometers for a passive spin. OPAL is uncontrolled but contains a passive energy damper so that a repeatable spin axis may be established for picosatellite deployments.

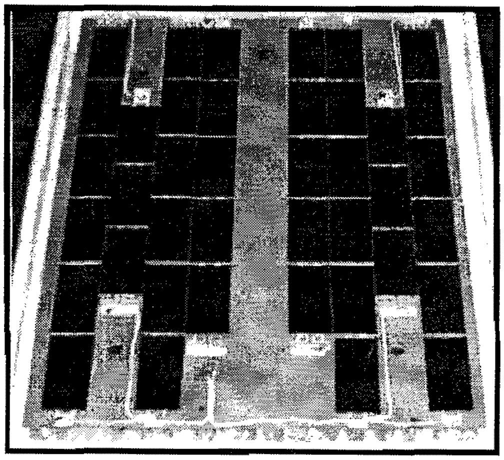

Figure 4 *- SAPPHIRE Test Solar Panel*

Thermal systems are completely passive and rely on the use of surface coatings, insulation, and influence on the choice of structural materials and configuration. SAPPHIRE's passive radiometric spin assists in smoothing thermal loads. OPAL could use it's actuators to execute low precision reorientations should it find itself in an undesirable sun pointing orientation.

Communications rely on amateur satellite frequencies and the use of AX.25 packet protocol for data transmission. SAPPHIRE utilizes a modified Hamtronics TA451 transmitter and R144 receiver and a Kantronics terminal node controller (TNC) at 1200 baud. OPAL uses NAVSYMM TNC and transceiver units at 9600 baud. Both spacecraft include a low power beacon.

Command and data handling for both spacecraft are executed by Motorola 68332 based Vesta computer boards that monitor and control component activity, process commands, and format telemetry. SAPPHIRE is currently equipped withh 256K of ROM and 128K of RAM.

SQUIRT Program Evolution

The long term goal of the SQUIRT program is to establish an programmatic infrastructure enabling the yearly production of research capable microspacecraft in a viable educational setting. In order to evolve to this point, several target areas for improvement have been identified. These consist of technical capability, development tasks, and project management and control.

Technical Capability

Although SQUIRT spacecraft will always be limited to low mass, power, and volume components, the realm of potential payloads can be expanded by focusing yearly technical upgrades along particular paths.

First, boosting communications bandwidth will allow more data intensive payloads to be considered and will increase the efficiency of spacecraft operations. OPAL has taken a solid step along these lines by upgrading to a system with eight times the data rate of the SAPPHIRE system. Along similar lines, increasing the coverage of the ground segment will provide more potential contact time with the satellites. Agreements have recently been made with affiliated academic programs to share ground station resources via Internet based coordination and control.

Second, increasing the maturity of the attitude determination systems will open up an entirely new class of payloads for consideration. Current SQUIRT systems are capable of only low precision single axis pointing information; much of this is not performed realtime (note that the requirements for the current vehicles do not require more precise information). Advancing the SQUIRT attitude control options would also broaden the capability of future missions. Advances are being focused on gravity gradient stabilization, simple reaction wheel systems, and magnetic methods. Potential propulsion payloads are also being considered for both attitude and position control.

Third, advanced processing capability is being pursued. Both current designs are continually attempting to increase the capacity and integrity of their memory banks; radiation hardened memory chips are being sought and error detection and correction systems are being designed. And while the Motorola 68332 microprocessor is powerful enough for the current vehicles, a variety of other computing systems are always being considered. Finally, spacecraft autonomy is an active area of research in SSDL; the products of this work will be targeted to provide robust fault processing, planning/scheduling, and executive functions on future SQUIRT spacecraft.

Development Tasks

The maturation and formalization of various developmental aspects of the design activity is being pursued in order to produce more predictable, capable, and useable spacecraft. Much of this effort is currently focused in the areas of design simulation, system test, and vehicle operations.

Due to the lack of resources and time, simulation and the composition of analytic models was fairly limited early in the SAPPHIRE design. As the necessary software packages were acquired, simulation was integrated into the SAPPHIRE project for the purposes of verifying and potentially redesigning components and subsystems. OPAL has adapted and added to this simulation toolbox in support of their design activities. Current simulation capability consists of structural and thermal finite element modeling, orbit and attitude dynamic modeling, and power subsystem modeling of various spacecraft operating modes.

A formal test plan has recently been assembled for the SAPPHIRE project and is being adapted for early integration into the OPAL project. Tests address concerns in the areas of integration, qualification, and verification. Environmental test opportunities are being developed for structural vibration, thermal balance, vacuum performance, radiation susceptibility, and acoustic integrity. A shake test model of the SAPPHIRE structure has been successfully tested to Delta launch vehicle standards.

Similarly, an extensive operational plan is being applied to all aspects of the SQUIRT mission architecture. This plan includes the formulation of both ground based and onboard procedures for launch integration and separation, payload functioning and data delivery, bus housekeeping and fault handling, and ground station nominal and contingency situations.

Project Management and Control

In order to successfully meet the goals of the program, a formal but practical management strategy is being evolved. This strategy hopes to adapt industry standard management objectives in a way that can be easily implemented in a student environment. At the same time, practices are being modified so as to be applicable to highly integrated design teams in a faster, cheaper, and better design paradigm. A successful process will enable the acceleration of the development timeline and establish sound methodology for managing risk.

The first effort in this regard is the composition of a project roadmap that integrates the execution of detailed design, simulation, integration, test, and operations planning. Such a product will provide a framework for new project teams and will be useful for gauging the progress of spacecraft development. The second effort concentrates on controlling the state of the design and establishing sound team communications. While SAPPHIRE has suffered at times from inadequate baseline design control, the OPAL team has initiated a formal process that fully documents and controls changes to the physical and electrical attributes of their system

The SQUIRT program has attracted a great deal of attention for its multidisciplinary, repeatable, and incremental approach. As a result, a variety of industry affiliates and design groups have proposed experiments involving management techniques and systems engineering methodologies. In the future, these experiments will be integrated into the program thus allowing SQUIRT projects to be a testbed for the design process as well as for research payloads.

Experiences and Lessons Learned

After only 18 months of existence, experiences with the SQUIRT program offer a number of interesting observations. These relate to program popularity, prerequisite experience, documentation and communications, and timely completion of projects.

First, the project has met with overwhelming popularity among students, academic institutions, and industry. Over 100 students have participated in one of the two current SQUIRT projects. These students have come from every engineering department at Stanford, from the business and engineering management departments, from non-engineering departments such as art and chemistry, and even from other schools such as Yale University and Tuskegee University. And while the project normally grants credit for only four courses, most students stay with the project beyond this point on a purely volunteer basis. Other schools have expressed interest in the format of the program and are building similar capabilities. Finally, SSDL's industrial affiliates have implemented special recruiting arrangements regarding students and have even explored ways to integrate their own professional development efforts with SQUIRT projects.

Second, experience with systems engineering fundamentals prior to participation in a SQUIRT design project has proved to be invaluable. To meet this need, the SSDL teaches an introductory spacecraft design course which is usually taken by students before becoming members of a satellite team. This is a project based course that requires students to use formal management and systems level practices in the technical design, construction, test, and remote operation of a fully functional albeit non-space capable "satellite".[3] Students with such a background have been found to be far more valuable in a multidisciplinary team environment.

Third, attempts to use electronic systems for realtime design documentation and project management have been largely unsuccessful. The current SQUIRT teams have experimented with electronic methods ranging from word processor based design logs to World Wide Web (WWW) based design control. For the most part, these techniques have proven too cumbersome in the current environment for the purposes of capturing the up-to-date system design. They are still used in order to provide continuity and low frequency updates to work being performed. For effective up-to-date design control, the OPAL team publishes electronic based schematics, data, and procedures. Daily changes and revisions are hand-drawn on the published documents. Each week, these changes are formally approved by all subsystem managers. The electronic documentation is then updated and republished for display.

Fourth, the use of electronic communications has been found to be very useful. Student academic schedules effectively create a team with all members working about one quarter time and with minimal overlap of availability. For this reason, electronic access to team members helps to keep collaborators in touch, provide convenient updates on project status, and solve conceptual problems in a virtual group setting.

Fifth, although the goal of the project is to eventually have satellites ready for launch within twelve months, the current group overlap between the SAPPHIRE and OPAL teams has been extremely beneficial. It was always assumed that projects would utilize and adapt previously designed components and subsystems in order to save time. But immediate access to the previous design team in a fully functional state has permitted the OPAL team to get a more natural and deeper feel for the process, trade-offs, and challenges of successfully completing their project. Because of the accomplishments and the strong presence of the SAPPHIRE team, the OPAL project is progressing at about 30% faster than SAPPHIRE.

SSDL Initiatives

The SSDL is actively promoting the development of an international academic microspacecraft community engaged in the rapid design, fabrication, and operation of microsatellites for educational and research purposes. This effort has involved SSDL personnel in the development and teaching of a comprehensive spacecraft design course at the University of Umea in Sweden. A similar program has recently been initiated with Tuskegee University in Alabama. Also, San Jose State University students have interned as engineers on SQUIRT projects in order to apply the experience to their own SQUIRT-like microspacecraft known as SPARTNIK.

Another initiative consists of building a WWW based interface for satellite payload commanding and data analysis. Research in this area is currently underway with Weber State University and the Ames Computational Sciences Division. Target spacecraft for this project include both WEBERSAT and laboratory based SQUIRT vehicles.

To promote such academic activities, the SSDL publishes program information and SQUIRT design data on the WWW at http://aa.Stanford.EDU:80/~ssdl/.

Conclusions

Progress in the SQUIRT program is quite promising. In only 18 months, the

SAPPHIRE design team has initiated the final fabrication and test of the SSDL's first microsatellite. This is particularly noteworthy given the project's initial resources of only five students, one room, no equipment, and no cash. Additionally, the SAPPHIRE team has built a solid program foundation by designing a flexible structural configuration, investigating and developing a range of viable bus components, and establishing an operational spacecraft development laboratory. The OPAL design team has built upon this work in order to rapidly progress to the integration of a novel technology flight demonstration. In only six months, this project has progressed from conception to functional prototype.

In order to improve the SQUIRT program's infrastructure, efforts are underway to evolve the technical capability of future spacecraft, improve and expand the variety of developmental processes, and formalize and control the management structure. Additionally, the program actively seeks to improve itself based upon its successes and failures. By evolving in this manner, the SQUIRT program will be able to successfully meet the educational needs of graduate students by blending systems engineering and hands-on technical experience.

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Author Biographies

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Mr. Kitts is a doctoral candidate in Stanford's Department of Mechanical Engineering Design Division. As a Stanford Integrated Manufacturing Fellow, he conducts research in spacecraft system design and control; his specialties are spacecraft autonomy and the cooperative control of satellite constellations. As the Graduate Student Director of the Satellite Systems Development Laboratory, Mr. Kitts manages the Satellite Quick Research Testbed program and assists with the development of spacecraft design curricula.

Prior to entering graduate studies at Stanford University, Mr. Kitts served as an Air Force officer in the Air Force Space Command. In this capacity, he commanded a mission control team responsible for the Defense Satellite Communications System III spacecraft constellation. He also served as a Chief of Academics for Space Command's premier space training school. Mr. Kitts received a BSE degree from Princeton University, an MS degree from Stanford University, and an MPA degree from the University of Colorado. He is currently a Caelum Research Corporation employee at NASA Ames Research Center working in the field of spacecraft systems engineering and autonomy.

Robert J. Twiggs

Prof. Twiggs is the director of the Satellite Systems Development Laboratory in the department of Aeronautics and Astronautics at Stanford University. He joined Stanford

University in December 1993 and is directing the satellite development activities in the department to develop microsatellites as a one-year project with engineering students and direct programs for the development of larger satellites to be used to support scientific payloads.

Prior to joining Stanford University, Prof. Twiggs was the director of the Center for AeroSpace Technology at Weber State University in Ogden, Utah. This center has been involved in the development, launch and operation of low cost small satellites since 1982 and supports the engineering technology program in the College of Applied Science and Technology.

Prof. Twiggs received a BSEE degree from the University of Idaho and an MSEE degree from Stanford University. He has worked in the microwaves field for Varian Associates, Teledyne and Microwave Associates. He worked in software development for Tymshare, National Semiconductor and TRW before joining Weber State University in 1981.