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We are pleased to report that the SCU team successfully developed a working prototype for the entire spacecraft as per our original proposal with the lone exception being the inclusion of an integrated lens assembly - diffraction grating that was to be used on our science camera for the purposes of taking multi-spectral images (this assembly was never delivered by our partners at the Jet Propulsion Laboratory). Apart from this exception, the ONYX vehicle conformed to all IJNP prototype specifications, and all required functionalities of the integrated prototype were wirelessly demonstrated. In addition to the science camera, payload demonstrations included a test bed to demonstrate advance anomaly management capabilities, a distributed command and data handling system, and an educational thermal control experiment. Furthermore, the SCU team participated in all UNP design reviews and auxiliary events in order to take full advantage of the educational experiences offered by the UNP. This report does not attempt to detail the design of or the processes used to develop the ONYX space system. For a technical program summary, a copy of the Flight Competition Review presentation slides are presented here as an attachment. Additional programmatic and technical documentation has been previously provided via FTP to the program file server. In addition, the references section of this report summarizes additional papers and student thesis documents that detail the development and technical design of the ONYX space system.

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FINAL PROJECT REPORT

(NANOSAT) The ONYX Nanosatellite Mission

Sponsor Award Number: FA9550-05-1-0249

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FINAL PROJECT REPORT

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Objectives: Over the period Spring 2005 – Spring 2007, students, staff and faculty from Santa Clara University's (SCU) Robotic Systems Laboratory participated in the U.S. Air Force's University Nanosatellite Program (UNP-4). As part of this program, this team developed the ONYX (ON-board autonomy eXperiment) nanosatellite. The objective of this project was to develop a nanosatellite prototype capable of performing several technical demonstrations, to include a) characterization and use of a novel snapshot multispectral imager for coastal ecological monitoring, b) on-orbit demonstration of advanced, automated anomaly management capabilities, c) benefits of a highly capable distributed command and data handling system, and d) the provision of an educational laboratory system demonstrating fundamental concepts in heat transfer and control theory.

Summary of Effort and Accomplishments/Results

We are pleased to report that the SCU team successfully developed a working prototype for the entire spacecraft as per our original proposal with the lone exception being the inclusion of an integrated lens assembly – diffraction grating that was to be used on our science camera for the purposes of taking multi-spectral images (this assembly was never delivered by our partners at the Jet Propulsion Laboratory). Apart from this exception, the ONYX vehicle conformed to all UNP prototype specifications, and all required functionalities of the integrated prototype were wirelessly demonstrated. In addition to the science camera, payload demonstrations included a testbed to demonstrate advance anomaly management capabilities, a distributed command and data handling system, and an educational thermal control experiment. Furthermore, the SCU team participated in all UNP design reviews and auxiliary events in order to take full advantage of the educational experiences offered by the UNP. This report does not attempt to detail the design of or the processes used to develop the ONYX space system. For a technical program summary, a copy of the Flight Competition Review presentation slides are presented here as an attachment. Additional programmatic and technical documentation has been previously provided via FTP to the program file server. In addition, the references section of this report summarizes additional papers and student thesis documents that detail the development and technical design of the ONYX space system.



*The integrated ONYX prototype,
without solar panels*

Personnel Supported

Funding for this program directly supported a part-time technical staff member, Mr. Bryan Palmintier. In addition, the work performed as part of this program benefited the PI, Dr. Christopher Kitts, through the research performed in the process of conducting this program.

Publications (available in List of Publications at <http://rsl.engr.scu.edu>):

- [1] F. Rogers-Marcovitz and P. Williams. "DEEP: Dallas EEPROM Equipment Profile for Rapid Integration and Automatic System Modeling." To appear in Proceedings of the AIAA/USU Conference on Small Satellite, Utah, August 2007.
- [2] M. Lim, J. Vasicek, J. Crabtree, M. El-Kassed, J. Mendoza, S. Moraleda, W. Nguyen, F. Parviz, B. Asher, D. Dennis, A. Nanda, A. Gulick, and J. Shepard. The ON-barod autonomy eXperiment (ONYX) space system. Advisor: C. Kitts. SCU Undergraduate Thesis, Departments of Mechanical, Electrical and Computer Engineering, June 2006.
- [3] F. Rogers-Marcovitz and P. Williams. "DEEP: Dallas EEPROM Equipment Profile for Rapid Integration and Automatic System Modeling." Proceedings of the Responsive Space 5 Conference, Los Angeles CA, April 2007.
- [4] B. Duda, L. Hagiwara, W. Le, B. Wat, E. Eklund, and C. Walker. Onboard Autonomy Experiment (ONYX) Space System. Advisor: C. Kitts. SCU Undergraduate Thesis, Departments of Mechanical and Electrical Engineering, June 2007.
- [5] R. Angeles, P. Williams, and Z. Zabinski. ONYX Nanosatellite Command and Data Handling Systems. Advisor: C. Kitts. SCU Undergraduate Thesis, Department of Computer Engineering, June 2007.

Interactions/Transitions

Interactions that occurred as part of this program included the following:

- Participation in all UNP design reviews
- Participation in the UNP SHOT workshop
- Participation in the 2005 AIAA/Conference on Small Satellites, Logan, Utah
- Participation in the 2006 AIAA/Conference on Small Satellites, Logan, Utah
- Participation in the 2007 Responsive Space Conference, Los Angeles, CA
- Planned participation in the 2007 AIAA/Conference on Small Satellites, Logan, Utah (student paper on UNP4 work to be presented)
- Interaction with personnel from the Jet Propulsion Laboratory relevant to work on the multispectral imager payload.
- Interaction with personnel from Washington University in St. Louis who adopted SCU's distributed command and data handling system for their UNP4 development efforts.
- Interaction with personnel from the University of Texas, Austin who adopted SCU's distributed command and data handling system for their UNP3 spacecraft, which is in the process of being prepared for future flight.
- Interaction with personnel from NASA Ames Research Center's new Small Spacecraft Office regarding our nanosatellite development work, our operations systems, etc.
- Interaction with local high school educators relevant to the thermal control chamber payload that was developed for the spacecraft.

New discoveries, inventions, or patent disclosures

None resulting from this funding program. However, an intellectual property disclosure is being planned for an advanced form of the distributed command and data handling technology that was demonstrated in part on this program.

Honors/Awards

- Student Phelps Williams won a student scholarship award to support presentation of a student paper at the 2007 Responsive Space 5 Conference.
- Two ONYX Project students received Technical Excellence Awards from the SCU Department of Computer Engineering for their work on the ONYX computer system.
- Project students on the 2007 ONYX Mechanical Engineering team won Best of Session honors in SCU's annual Senior Design Conference.
- Project students on the 2006 ONYX Mechanical Engineering team won Best of Session honors in SCU's annual Senior Design Conference.
- Project students on the 2006 ONYX Electrical Engineering team won Best of Session honors in SCU's annual Senior Design Conference.

University and Program Impact

The following are responses to the impact questions that each PI has been asked to address regarding the effect that participation in the UNP program has had on the host institution.

1) How many years has your Department or Research Program been participating in the University Nanosatellite Program? We have participated in NS-1 (Emerald, in cooperation with Stanford), NS-3 (we were not a primary school, but we teamed with UT Austin and Washington Univ in St. Louis and provided both schools with their distributed computing / flight processing subsystems), and NS-4 (ONYX, plus we again provided distributed computing avionics to Washington Univ).

2) What impact has this participation had on the following factors? Please provide any illustrative information to support these conclusions if possible. Overall - our participation in UNP has been a significant element in my lab's "portfolio" of hands-on, interdisciplinary projects (my lab's web site is at <http://rsl.engr.scu.edu>). We have a field robotics program in which our students develop and operate underwater robots, land rovers, UAVs, and spacecraft. With respect to spacecraft, we are involved with projects ranging from 100% student built projects (like our UNP work) to project in which we are full-fledged team partners with NASA and industry (such as our work with GeneSat-1, PharmaSat, etc.... Class D NASA missions). The UNP projects have served as a wonderful experience for our undergraduates - typically through year-long senior design projects - and these students often wind up getting jobs in the local aerospace industry (Lockheed, NASA Ames, etc.) or go to grad school (many often stay at SCU

for grad school, and most of our grad students working on more sophisticated spacecraft projects started on a UNP project).

a. Your personal research program as a professor (e.g., good, productive use of your time and resources, building momentum, helping or hindering the furthering of your research agenda?) I have been able to leverage my research with these projects by incorporating advanced technology demonstrations into the missions. I think this is a critical element for long-term success given that I am a tenure-track faculty member.

b. The Department in general (e.g., correlation with enrollment, acquiring new labs, equipment, or facilities, etc. etc.) Although I would hesitate to chalk results up as a direct result of UNP, our overall work with hands-on spacecraft projects (again, ranging from UNP to Class D NASA projects) has established our regional reputation in this area. This has led to a new, substantial partnership with Lockheed in which we are now teaching a graduate sequence of courses on space systems - in Spring 2007, this class had a grad enrollment over 50, which made it the most popular graduate class in the entire School/University! Partnerships like this (with Lockheed, with NASA, with CSA, etc.) have led to a substantial increase in our research funding as well.

c. School or University at Large (e.g., initiating a new department, closing one down - although I hope not!) See above.

d. The students who have worked on the program (any information you are aware of on positive or negative impacts the program had on students would be helpful) MANY of my graduating undergrad students wind up going to work in the aerospace industry (Lockheed, NASA, Boeing, etc.), going to graduate school (SCU, Stanford, Cornell, etc.), or wind up as engineers in non-aerospace high tech industries such as IT. Furthermore, we have a substantial part-time graduate student program in which these students are full-time engineers in the local aerospace industry. I could rattle off a list of students who have declared themselves that they have pursued careers in aerospace as a direct result of their experience with our hands-on spacecraft projects. Although it may not be of primary interest, I should also point out that we have a similar percentage of students who work on non-space-related robotics projects (like our UAVs, rovers, marine robots, etc.) and who wind up pursuing aerospace careers; these projects have similar educational elements in the sense that they are real-world, hands-on, interdisciplinary, mission-oriented, etc.

Flight Competition Review Presentation Slides



Robotic Systems Laboratory



University Nanosat 4 Flight Competition Review March 27, 2007



SCU ONYX FCR

- ONYX Mission / Technical Relevance
- Bus Overview
- System Analyses
- Operations
- Student Participation
- Closing Remarks



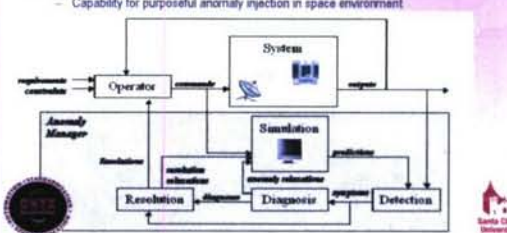

ONYX Mission Statement:

During a 45 day nominal on-orbit mission, the ONYX space system will operationally validate advanced, distributed space system development and autonomous control techniques while conducting an Earth observing mission and providing educational services for university and K-12 students.




Anomaly Management: Model Based Reasoning

- Model Based Reasoning (MBR)
 - Testbed for new reasoning approach in performing anomaly management
 - Provides inexpensive alternative tool for operational practices
 - Intelligent detection, diagnoses, and resolution using first order principles
- Controlled in-situ space experimentation
 - Capability for purposeful anomaly injection in space environment






Rapid Integration & Standardization: distributed Command & Data Handling

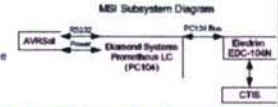
- Distributed CDH framework based around Emerald Protocol suite standard
 - Standard Intra-satellite communication Protocol
 - Standard Satellite ↔ Ground; potentially Satellite ↔ Satellite Radio Protocol
 - Standard Hardware Interface Protocol
 - Standard Hardware configuration and control protocol
- Demonstration of Rapid Integration and Test (RIT) capabilities
 - Result of standardization in bus design
 - "Black box" RIT Payload from Washington University
- Demonstration of modular AVR-SAT hardware
 - Requires minimal modification for use throughout satellite
- Demonstration of rapid development, integration, and test for space environment
 - Utilizing unique stresses of the space environment to fuel future SCU research and development of bus standardization (Automated Bus Configuration)






Scientific Instrumentation: Low Cost Multi-Spectral Imaging

- JPL Computing Tomography Imaging Spectrometer (CTIS)
 - Low power, low mass, low volume, low pointing requirements
 - Multi-spectral snapshots
- COTS Imaging Hardware
 - Demonstrating low cost COTS hardware
 - Demonstrating rapid COTS integration into standard bus
- Completes the RSL vision
 - Multi-environment capabilities with space-based scientific instrumentation





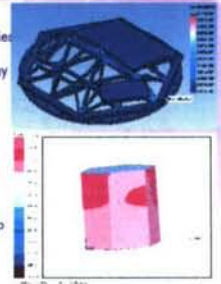

Design Overview:

- **Structure:**
 - Aluminium isogrid provided by WUSTL
 - Aluminium honeycomb substrate for solar panels
 - Trays isolate bus components from payloads
 - EMI enclosures facilitate integration
- **Thermal:**
 - Primarily passive design
 - Strip heaters for sensitive subsystem control
- **Attitude Determination & Control**
 - Passive magnetic stabilization
 - Light sensors and solar panel current sensors
 - Accurate and near real-time attitude determination



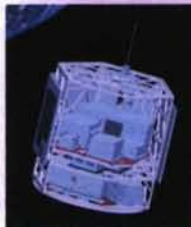
System Analyses

- **Mech. Stress Analysis:**
 - High-res. FEA performed for tray assemblies
 - Minimum FS = 3.8 @ walls
 - Min Natural Frequency: 259 Hz @ top tray
- **Thermal Analysis:**
 - Low-res. FEA performed for satellite
 - Temp Range = 270–287 K
 - Highest region: solar panels
 - Lowest region: bottom plate
- **Mass Budget:**
 - Currently: 26 kg
 - CG: < 1/4" from centerline, < 12" above SIP
- **Volume Budget:**
 - RFDW: Antenna outside volume
 - RFDW: Solar panel below SIP



Design Overview: (cont'd)

- **distributed Command & Data Handling**
 - Primarily composed of AVR-Sat modules
 - Emerald Protocol Suite standard
 - Provides bus control and telemetry acquisition
 - Event scheduling and telemetry monitoring
- **Communications**
 - 70cm uplink/downlink COTS radio
 - 5W transmit power
 - 9600bps
- **Power**
 - Emphasis in reliability and safety to primary vehicle
 - Significant telemetry based performance feedback
 - 8 body-mounted solar panels



System Analyses: (cont'd)

- **Link Budget:**
 - Uplink Margin: 12.7 dB
 - Downlink Margin: 13.6 dB
 - Modulation: DRCMSK (proprietary)
- **Computing Budget**
 - Average runtime memory usage ~ 56%
- **EMI Analysis**
 - Metal enclosures used to limit subsystem interference
- **Power Budget:**
 - Analysis performed on LEO orbits of Sapphire (NO-45) and GeneSat-1
 - Positive margins in nominal operations under worse case orbital conditions
 - Power system life will exceed primary mission span
 - Mean power generation in nominal operations: 8.21W



Flyability

- **Materials, components, and hardware provided with certifications of compliance, first article inspections, and shop orders**
- **Power system designed in accordance with UNP**
- **Structure designed in accordance with UNP**
- **Complete MGSE & EGSE designs**
- **Sandy Goin assisting in Proto-Flight Assembly**
 - SCU RSL Clean Room Manager
 - NASA Certified Instructor
 - 35+ Years of experience



Student Participation & Education

- **Participation of 100+ SCU students**
 - Engineering, Physics, Comp. Sci, Accounting, Marketing
 - Undergraduates through Ph.D
 - Emphasis on undergraduates
 - Supporting hands on education in: project management, system engineering, design, analysis, fabrication, testing
- **Inter-University collaboration**
 - Washington University in St. Louis
- **Educational Outreach Thermal Experiment Payload**
 - Designed to be utilized in University or High School Lab scenarios
- **Educational Outreach**
 - Raising profile of University Class missions
 - Training next generation of scientists and engineers
 - Encouraging excitement and interest in space technology development
 - 1000+ K-12 Students already involved in ONYX Program



Operational Capabilities

- **SRI Antenna Facility**
 - 80 foot parabolic dish
 - >35dB gain at 70cm
- **Remotely Controllable OSCAR Framework**
 - 17dB 70cm Yagi on Az/El controller
 - Active amateur radio mentors
 - Automated tracking and link logging
 - Additional nodes rapidly deployable
- **Trained group of student operators**
 - Training and Certification Program in place
- **Functional and in use on daily basis**
 - Operational software framework in place
 - Minimal modification required for ONYX
- **Established community support fostered through GeneSat-1 success**
 - Over 60,000 submitted telemetry packets by public
 - 40+ Operators from 17 countries



On-orbit Operational Phases

- **Initialization Phase**
 - Estimated Length: 1 Week
 - Charge Batteries
 - Allow orbital predictions to mature
- **Health Assessment Phase**
 - Estimated Length: 1 Week
 - Determine health of individual subsystems
 - Verify operation within expected bounds
- **Experiment Phase**
 - Expected Length: 4 Weeks
 - Gather mission critical data products
- **Nominal Extended Operation Phase**
 - Expected Length: Until EOL
 - Extension of Experiment Phase beyond mission critical data
 - Bus stress testing

Experiment Phase Detail

Execute AMT Experiment
Capture and Download 1 Multi-Spectral Image
Characterize spacecraft attitude using PADCI
Coordinate EDU in class lab environment
Operate RIT as defined by WUSTL



Santa Clara University: ONYX

- Capable satellite, in accordance with UNP specifications & industry recommendations
- Proven operations capability
- **Student involvement:**
 - Educated university students in all project roles
 - Inspire K-12 students to join sciences and engineering fields
- **Technical Relevance:**
 - **Anomaly management:** Model Based Reasoning
 - **Rapid integration & standardization:** Emerald Protocol Suite
 - **Scientific instrumentation:** Autonomous control of low-cost multi-spectral imager, ideal for small satellites



Requirement Verification Matrix

Subsystem	Primary Requirements	Risk Assessment
AMT	G	G
MSI	R	Y
EDU	G	G
RIT	G	G
STR	G	G
THM	G	G
dCDH	G	G
COMM	G	G
EPS	G	G
ADC	G	G

*Minor hardware modifications required for flight

G = verified **Y** = pending verification **R** = req. further dev.



RACE Architecture

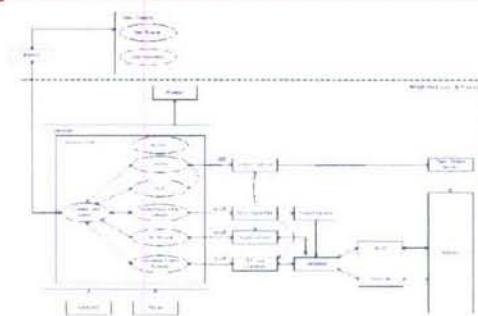


Figure 1.0: RACE Architecture Block Diagram

Stress Analysis: Model Verification

- Clamped plate: 420 x 420 mm
- Assumed thickness: 3.175mm
- Evenly distributed load: 7 kg * 20g/s
- Max Displacement: 1.49mm
- Max Stress: 41.9 MPa

