MICRO- AND NANOTECHNOLOGY APPLICATIONS AT STANFORD UNIVERSITY

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Abstract - This paper describes the on-going and upcoming SQUIRT (Satellite Quick Research Testbed) satellite projects at Stanford University and their relation to micro- and nanotechnologies.

The advances in micro- and nanotechnologies open numerous possibilities for space applications that perhaps would otherwise be too difficult to implement with conventional technologies. MEMS devices holds advantages in its operational requirements over conventional technologies.

Along with their promise to advance the state-of-the-art in space systems and research, the advantage of MEMS devices are even more important considering the limitations inherent to university-built satellites.

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1. INTRODUCTION

Micro-electromechanical systems (MEMS) and other nanotechnologies enable satellite size to shrink enormously while still offering equal or even improved performance. This opens up new possibilities from closely coupled yet distributed multi-satellite "formation flying" to capable picosatellites small enough to hold in the palm of your hand. At the same time MEMS promises to help more traditional space systems by extending mission capabilities, reducing costs, and shortening the design life cycle. Microsatellites benefit from the size, mass and power savings generated by the new technologies. In return, these technologies obtain inexpensive and easy access to space to test their concepts and provide flight heritage.

Stanford University's Space Systems Development Laboratory (SSDL) has been involved in micro- and nanotechnology since the first microsatellite, SAPPHIRE, which is a testbed for MEMS Tunneling Infrared Horizon Detectors. With its third and fourth microsatellite, SSDL is exploring new mission architectures that could be enhanced by nanotechnologies while continuing to provide more sophisticated testbeds for state-of-the-art technologies.

The second microsatellite, OPAL, is named after its primary mission as an Orbiting Picosatellite Launcher. OPAL will explore the possibilities of the mothership-daughtership mission architecture using the SQUIRT bus to eject palm sized, fully functional picosatellites. OPAL also provides a testbed for on-orbit characterization of MEMS accelerometers, while one of the picosatellites is a testbed for MEMS RF switches.

EMERALD is the upcoming SQUIRT project involving two microsatellites, which will demonstrate a virtual bus technology that can benefit directly from MEMS technology. Its payloads will also include a testbed dedicated to comprehensive electronic and small-scale component testing in the space environment. EMERALD will also fly a colloid micro-thruster prototype, a first step into the miniaturization of thruster subsystems that will eventually include MEMS technology. The thruster is being developed jointly with the Plasma Dynamic Laboratory at Stanford University.

2. THE SPACE SYSTEMS DEVELOPMENT LABORATORY

Since its conception, the Space Systems Development Laboratory (SSDL) has been a leader in improving the design of space systems. The university environment encourages new approach to the design challenges of space systems.

The SQUIRT (Satellite Quick Research Testbed) program emphasizes the design, construction and operation of a 25-pound, 12-inch high by 17-inch diameter hexagonal satellite bus for under $50,000. Students lead all aspects of the project, from engineering and design to management, with faculty and industry mentor oversight. The program is built around the Department of Aeronautics and Astronautics Master of Science Degree curriculum. It is designed such that the students would be able to see the entire life cycle of a spacecraft. Those who opt for a more advanced degree would have the opportunity to incorporate their research into the subsequent spacecraft.

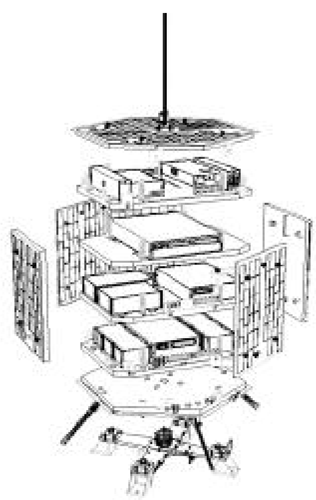

Figure 1. SQUIRT Microsatellite Bus

Under the SQUIRT program, much emphasis given in spacecraft design and engineering is aimed toward the use of low-cost, commercial off-the-shelf (COTS) components. Even though COTS technologies may have inherent disabilities for space operation, they are cost effective and sometimes are more advanced than their space-qualified counterparts. The latest commercial technologies allow the performance envelope to be pushed further, resulting in highly capable spacecraft that are cost-effective with a quick turnaround.

At the same time, this unique approach opens opportunities for these COTS technology to be tested for their suitability in space application. The end result is a cycle that is mutually beneficial for the aerospace community and the commercial industry.

In particular with MEMS, SSDL provides testing platforms for MEMS devices as well as providing flight heritage. SSDL is also exploring new space architectures that will be greatly enhanced through the use of MEMS devices.

MEMS devices also serve as a payload that is easy to integrate and fits within the requirements of student spacecraft. It also provides research opportunities for students pursuing an advanced degree.

3. SAPPHIRE MICROSATELLITE

SAPPHIRE is the first microsatellite designed and built at SSDL. SAPPHIRE is an acronym for Stanford Audio-Phonic Photographic InfraRed Experiment. Its primary payload is a MEMS Tunneling Horizon Detector (THD) built by Stanford Micro Structures and Sensors Laboratory. Figure 2 shows the complete THD sensor package.

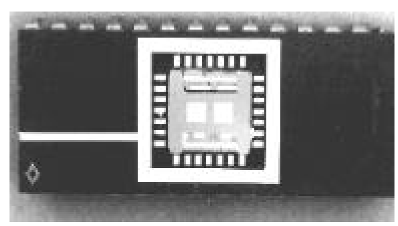

Figure 2. THD sensor in a 28-pin package

THD CHARACTERIZATION

The THD uses the principle of electron tunneling, where electrons jump between two electrodes that are held at a distance of tenths of Angstroms. The electrodes consist of a membrane and a tip that have an initial separation of about 1-micron. Application of a large voltage on the electrodes creates electrostatic force that pulls the membranes closer and allows electron tunneling to begin.

For the horizon detection application, a chamber of gas is constructed such that its volume is related to the position of the tunneling membrane. When the sensor is exposed to an IR radiation, the gas is heated and expands. The expansion of the gas chamber applies pressure to the membrane, causing it to deflect. Figure 3 show a more detailed view of the tunneling sensor.

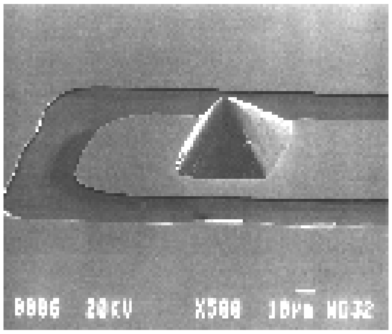

Figure 3. A close up view of the Tip Electrode.

The force on the membrane can be measured using the electron tunneling current, which translates to a measure of the change in IR signal. For this application, it is the change between the IR signature of the earth and deep space. The change of this signal translates to the crossing of the Earth's horizon.

SAPPHIRE sets an example of the application of MEMS for space that is mutually beneficial. SAPPHIRE gives the flight opportunity for MEMS technology to test its applicability in space and allows MEMS devices to gain flight heritage. This flight opportunity is also used to collect on-orbit data that supports previous research done by students at SMSSL. To SSDL, MEMS makes it possible to incorporate such sensors into a package that makes an interesting payload that fits within the constrains set by a low-cost, student-built satellite program.

SPACECRAFT DESCRIPTION

Pictured in Figure 4, Sapphire weighs 40 pounds and is housed in an 11 inch tall, 17 inch diameter, modular, hexagonal, aluminum honeycomb structure. The power subsystem includes a single 10 cell NiCd battery, 5 and 12-Volt regulators and eight Gallium Arsenide 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.

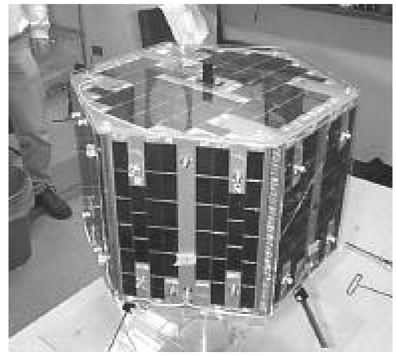

Figure 4. SAPPHIRE Microsatellite

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 vehicle spin. Commercial IR Photodiodes as Earth sensors provide attitude sensing. Passive thermal control is maintained through the vehicle's spin, insulation, coatings, and conductive materials. The satellite has a variety of secondary missions, which include communications broadcasting, Earth photography, and autonomous system technology demonstrations.

4. OPAL MICROSATELLITE

OPAL, the second SQUIRT satellite, both contributes to the testing of MEMS devices in space and benefits from MEMS characteristics. Two of OPAL's three payloads test the behavior of MEMS devices in space: the accelerometer payload and the picosatellite payload. In addition, the picosatellite payload investigates new mission architectures that will require the application of MEMS technologies in the future.

ACCELEROMETER

The accelerometer payload is a good example of the symbiosis between MEMS technology and SSDL's microsatellites. OPAL will carry two MEMS Analog Devices ADXL05 accelerometers, and will investigate their behavior in space. The devices measure changes in capacitance in a circuit etched on a silicon die to measure accelerations. The capacitance change is induced by a deflection of a MEMS element due to the acceleration. This accelerometer has very low power consumption and it comes in a small surface-mount package, making it very suitable for integration in a

SQUIRT microsatellite. Since it is already mass-produced for automotive air bag systems, it is inexpensive and readily available, something uncommon in most sensors used in space applications. By flying in the OPAL mission, the ADXL05 obtains flight heritage, while SSDL receives information on its performance in space. OPAL obtains a funding payload which is easy to integrate and operate, and which consumes minimal amounts of the spacecraft's scarce resources, such as power, mass and volume.

RF SWITCH

Two picosatellites built by the Aerospace Corporation and sponsored by DARPA will fly in OPAL and will have as their main mission to provide a testbed for MEMS technology. MEMS RF-switches will be flown in each of the Aerospace/DARPA picosatellites, and their performance in space will be investigated. These RF-switches hold great promise for application in communication systems. Their design is inherently radiation-hardened, and they can provide improved performance over conventional RF switches. By flying in OPAL, these RF switches can be tested in space in a cost-efficient fashion in a short-duration project

MOTHERSHIP - DAUGHTERSHIP MISSIONS

The use of MEMS provides benefits in today's space systems, but it can also enable new types of missions. The mission architecture investigated by OPAL, in which a mothership (OPAL) deploys several picosatellites that perform separate or coordinated missions, can draw many benefits from MEMS technologies. This type of architecture can accomplish a variety of missions with greater performance and robustness than single-satellite missions. By having several picosatellite daughterships, the mission greatly reduces the number of single-failure points and it can attain objectives that were not possible in the past. For example, a group of picosatellites can perform simultaneous measurements in several different points over a distributed volume, something that is not possible with single-spacecraft missions.

The primary objective of the picosatellite payload is to demonstrate the feasibility of a mothership technology mission. The OPAL design team developed a mothership system capable of storing and launching several picosatellites. These satellites, with dimensions as small as 4"x3"x1", will perform a variety of missions in space after being deployed by OPAL.

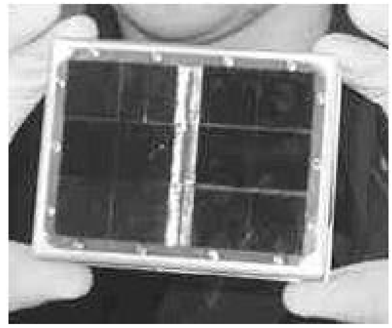

Figure 5. A picosatellite built by the Amateur Radio enthusiasts from Washington DC.

The picosatellites, which are built and designed outside SSDL, are related to MEMS in several ways. Figure 5 shows one of the picosatellites. All of them exemplify new types of low-cost nanosat missions that will be enabled by the use of micro- and nanotechnologies. One of these missions is the testing of the MEMS RF switch described above. The satellites that will provide the testbed for the RF switches will also demonstrate satellite constellation concepts. The Santa Clara University-designed Artemis picosatellites will be used to investigate Very Low Frequency (VLF) events in thunderstorms. Recent discoveries of sprites and blue elves in the upper atmosphere have generated great interest in the scientific community. The Artemis picosatellites will provide useful information about these phenomena. They will also prove that nanosatellites can produce useful scientific data at very low cost, and they will show the type of new missions enabled by micro- and nanotechnologies. The other picosatellite, built by a team of amateur radio enthusiasts, will use a transponder to enhance amateur radio communications. This picosatellite also shows an application for picosatellites that can draw from the MEMS developments.

The development of picosatellites is greatly enhanced by new micro- and nanotechnologies. The great reduction in size and power that is a main characteristic of MEMS fulfills some of the driving design parameters in picosatellites. The reduced size of picosatellites, on the order of a few inches, reduces their power generation capabilities, and places strict constraints on the power consumption of spacecraft components. Their size also places severe constraints on components' mass and volume. The low cost of MEMS devices also enhances the development of picosatellites. By providing low cost components, it is easier to investigate new missions and architectures, since lower-cost, higher-risk missions are possible.

MEMS also benefit from picosatellites, since they can obtain short design life cycle missions at costs much lower than standard missions. This type of quick turnaround test environment encourages the development of new MEMS concepts and allows their verification.

By investigating these new mission architectures, SSDL is not only providing validation for the applicability of MEMS in space. It is also generating a market for MEMS technology in the future. New architectures and missions that rely on picosatellites will generate a demand for new MEMS devices, which will fuel the development of new micro- and nanotechnologies.

SPACECRAFT DESCRIPTION

The OPAL spacecraft shares many similarities to its predecessor, SAPPHIRE. OPAL weighs approximately 42 pounds and measures 9.5-inch tall and 16.5-inch diameter. The power subsystem is similar to SAPPHIRE, with NiCd batteries and Gallium Arsenide cells. The communication subsystem uses off-the-shelf components and communicates through the amateur radio band at 9600 baud. A Motorola 68332 microprocessor, radiation hardened ROM and 1MB RAM comprise the central processing unit. The OPAL microsatellite, pictured in Figure 6, currently undergoes its final integration and testing. It is scheduled for launch on September 15, 1999.

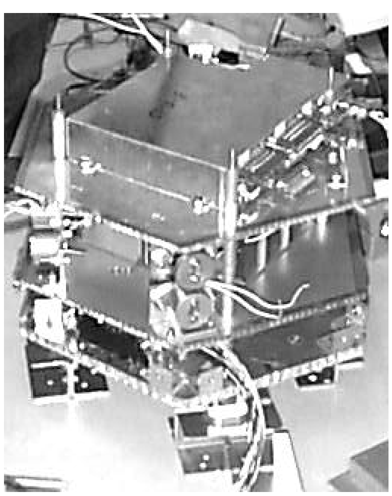

Figure 6. OPAL Microsatellite

The subsystem components are arranged in three modular trays that are vertically stacked. The bottom tray houses the power subsystem. The processor, communications, the MEMS sensors and additional secondary payloads, occupies the top tray. The picosatellite launchers are mounted on the second tray. The side mounted solar panels screw on to the internal trays. OPAL does not have any attitude control. However it does have solar pressure-induced spin along the picosatellites launch axis. OPAL's secondary missions include testing of additional COTS accelerometers. OPAL will also test a magnetometer for the Gravity Probe B Program, which is mounted on a 4-inch boom that extends from the top panel.

5. EMERALD MICROSATELLITES

The EMERALD mission is a joint two-satellite project being developed jointly by SSDL and Santa Clara University as part of the AFOSR/DARPA University Nanosatellite Program. These two spacecraft will demonstrate coarse formation flying capability through the use of GPS receivers, an inter-satellite communications link, and advanced microthrusters. Together, the two spacecraft will operate as a virtual bus in order to perform an ionospheric science mission consisting of the simultaneous reception of lightning-induced VLF radio emissions.

COLLOID MICROTHRUSTERS

The Colloid Micro Thruster (CMT) that will be flown on EMERALD will be the first step into miniaturization of propulsion units for micro- and nano-class satellites. The thruster works under the principle of electrostatic acceleration to generate its thrust. Due to its underlying principle, the CMT promises better system performance efficiencies for microsatellites when compared to other types propulsions systems.

The Plasma Dynamic Laboratory at Stanford University is currently leading the research into this type of propulsions. Data collected on-orbit will be used to validate research findings and to aid in the subsequent development efforts. MEMS technology has numerous possibilities that can be applied to enhance CMT systems. This will be explored on the next development phase.

MERIT RADIATION TESTBED

The Micro Electronics and Radiation In-flight Testbed will be the payload on one of the EMERALD satellites. MERIT will perform on-orbit operational testing for state-of-the-art technology such as MEMS.

These tests will provide data on the radiation hardness of these devices in the space environment. The data are also provided with quick turnaround time, which will be an added benefit for the subsequent development effort of these technologies.

VIRTUAL BUS ARCHITECTURE

Spacecraft formation flying is a technology in which a mission is performed by a virtual spacecraft comprised of a distributed array of simple, low-cost, highly coordinated vehicles such as a formation of small satellites. This is a dramatic departure from current monolithic bus architectures. Many scientific, military, and commercial space applications may be able to benefit from using a formation flying strategy in order to perform distributed observations for surveillance, Synthetic Aperture Radar (SAR) earth mapping, magnetosphere sensing, interferometry, and a variety of other missions. MEMS is an enabling technology for incorporating state-of-the-art sensing and control capability into such constellations given the more constraining limitations on mass, power, and volume for each member satellite.

Emerald will attempt to validate formation flying by performing a variety of functions. First, Emerald will serve as a low-cost, rapid prototyping testbed for component-level technologies crucial to the system level performance requirements of future formation flying missions. These component-level tests will include determining the accuracy and survivability of a low-power GPS receiver, evaluating the capability and robustness of an inter-satellite communications link, characterizing the performance of newly-developed microthrusters, and examining the value of very low-cost passive means of constellation position control such as tethers and drag panels.

Second, Emerald will use the aforementioned components to enable simple, closed-loop, on-orbit experimentation as the first step in Stanford's long-term program in spacecraft formation flying.

Third, Emerald will validate the formation flying concept by conducting a science experiment that can be enhanced through this technology. The science experiment consists of sampling lightning-induced Very Low Frequency (VLF) radio waves in order to study the ionosphere. Taking these measurements on physically distributed platforms with high accuracy relative position sensing and control contributes to the science that can be accomplished. This investigation is part of a broader small satellite-based ionospheric-science program being conducted by Santa Clara University and the Stanford Space Telecommunications And Radioscience Laboratory (STARLAB).

SPACECRAFT DESCRIPTION

The Emerald buses will use an enhanced version of SSDL's 12-inch tall, 17-inch diameter hexagonal SQUIRT microsatellite configuration. Drag panels will be incorporated into this design by actuating two opposite side panels. A radiation-tolerant Motorola 68332-based processor board, based on the SAPPHIRE and OPAL designs, will be used as the flight controller for both satellites. This processor has multiple serial ports, control lines, telemetry channels, and a proven student-developed operating system that includes an advanced expert system for automated platform control. Coarse attitude determination suitable to meet mission objectives, on the order of 5 degrees, will be provided with simple visible/infrared light sensors.

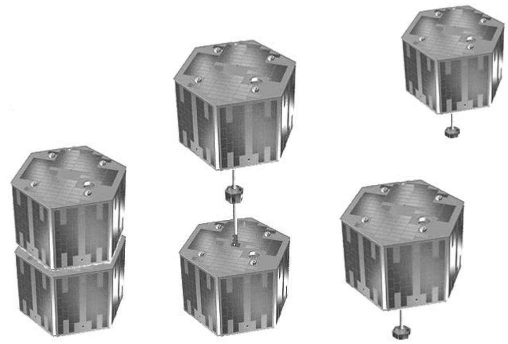

Figure 7. EMERALD Operational Phases

A 9600-baud or faster packet communications system will be used. The heritage power system consists of body-mounted solar panels and NiCd batteries. This system will provide 7 Watts of average power to components via a 5V regulated bus. Passive thermal control will be achieved through the use of insulation and thermal coatings.

Figure 7 shows the EMERALD microsatellites during its planned operational phases. The first phase is planned for system checkout. It will be followed by a tethered operation, which will be used to test the GPS relative positioning by using the known separation distance. Upon success of the second phase, the full relative position controlled formation flying experiments will commence.

6. CONCLUSION

The university environment contributes to the development of MEMS technologies by providing low-cost access to space. At the same time, MEMS is a very suitable payload for university microsatellites. They provide low-cost payloads that are easy to integrate and operate, while providing research opportunities for students.

These merits are evident in the past and present projects at the Space Systems Development Laboratory. SSDL continues to explore MEMS application for space as its technologies promise significant advancement in space system designs and architectures.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Kenny, T., and K. Stattenfield, "*Tunneling Sensors Description*", Engineer's Thesis, Stanford University, 1995.

Twiggs, R., and M. Swartwout, "*SAPPHIRE - Stanford's First Amateur Satellite*", In Proceedings of the 1998 AMSAT-NA Symposium, Vicksberg, MS, October 14-16, 1998.

Kitts, C., and R. Twiggs, "*Low Cost Space Mission for Education and Technology Research*", In Proceedings of the 21st International Symposium on Space Technology and Science, Omiya, Japan, 1998

Engberg, B., J. Ota, and J. Suchman, "*The OPAL Satellite Project: Continuing the Next Generation Small Satellite Development*", In Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September 19-22, 1995.

Cappelli, M., and F. Pranajaya, "*Colloid Micro Thruster Research*", Stanford University, Research Report, July 1997.

Kitts, C., R. Twiggs, J. How, F. Pranajaya, and B. Palmintier, "*EMERALD: A Low Cost Formation Flying Technology Validation Mission*", In Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, Colorado, 1999.