ORION: A MICROSATELLITE TESTBED FOR FORMATION FLYING

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Abstract A revolution in spacecraft guidance, navigation and control technology has started with GPS to autonomously provide spacecraft position, attitude and time information. This new technology is being applied to spacecraft constellations to achieve the precision formation flying required for many proposed science and commercial missions. These innovations will also result in significant reductions in weight, power consumption, and cost for future spacecraft attitude and orbit determination systems. Carrier-Phase Differential Global Positioning System (CDGPS) techniques can be used to autonomously track and then control the relative position and attitude between spacecraft. This sensing technology will enable the development of a virtual spacecraft bus where several spacecraft fly in close formation so that they can accomplish a common mission. This paper describes the capabilities being developed by merging the microsatellite and the CDGPS research at Stanford University. The focus of this cooperative laboratory effort at Stanford is on the Orion project, which will provide a low-cost microsatellite testbed to demonstrate precision formation flying.

Introduction and Motivation

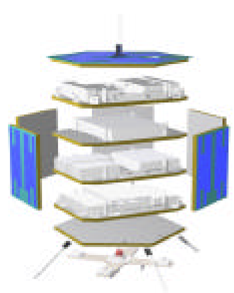
Several future space science missions are driving the need for small, low cost satellites that can fly in formation and perform collaborative observations. Our approach to the spacecraft guidance, navigation and control uses Carrier-Phase Differential Global Positioning System (CDGPS) techniques to autonomously track and then control the relative position and attitude between the spacecraft in the formation. GPS can provide both vehicle position and timing information, and thus should result in significant reductions in weight, power consumption, and cost of future spacecraft attitude and orbital determination systems. This will also provide significant improvements in the capability of future microsatellites, and will allow them to be used in very complex missions.

Recent results have demonstrated that Carrier-Phase Differential GPS (CDGPS) techniques can be used to autonomously track and then control the relative position and attitude between several spacecraft [1-8]. This sensing technology can be used to develop a virtual spacecraft bus using automatic control of a cluster of micro-satellites to replace the monolithic bus of current Earth Sciences Enterprise (ESE) satellites (such as Landsat-7) [3,6]. Many future space applications would benefit from using this formation flying technology to perform distributed observations, including earth mapping (SAR, magnetosphere), astrophysics (stellar interferometry), and surveillance. The goal is to accomplish these science tasks using a distributed array of many simpler, but highly coordinated, vehicles (e.g., micro-satellites).

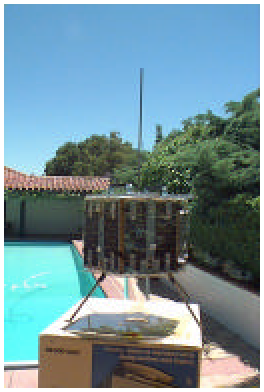
The Space Systems Development Laboratory established in 1994 has been developing low cost microsatellites. The Aerospace Robotics Laboratory and the Space Systems Development Laboratory are now combining efforts to develop the technologies and hardware for a fleet of low-cost spacecraft to demonstrate precision formation flying. This combined effort is the NASA Goddard Space Flight Center sponsored Orion Project.

Space Systems Development Laboratory

The goal of the Space Systems Development Laboratory (SSDL) is to de-emphasize the large-scale method of thinking and replace it with the philosophy that space-faring vehicles can be designed and built to be smaller, faster, and cheaper, while still undertaking contributive tasks and experiments. Such satellites need to be small, lightweight, modular, and still offer full hardware support (power, CPU, attitude control, *etc.*) for what-ever payload is to be integrated on board. The result is a class of satellites named SQUIRT [9], which is an anagram for Satellite QUIck Research Testbed. The outline design of these satellites calls for a weight of 25-40 pounds and a size of a hexagonal cylinder 16-18 inches in diameter by 9-12 inches high. The internal structure of the satellite consists of a series of stacked trays. This satisfies the modularity requirements and allows for easy access to components. The total cost of each satellite is targeted to be less than $50K. Finally, one very important emphasis in SSDL is to work towards a goal of a one-year microsatellite development time. This means that a SQUIRT should be conceptualized, designed, and built all within one calendar year. SQUIRT satellites obviously cater to experiments that are small and require limited power, but by no means does this limit their capability. There are many sensors and small experiments waiting to be flown that would otherwise be forced to wait until they could be incorporated into a larger project or shuttle mission. In fact, the SQUIRT [10] restrictions could actually help the space industry in the sense that potential equipment to be flown on board will have an incentive to be designed smaller, more power efficient, and less costly.



SAPPHIRE Concept



Final Antenna Testing – SAPPHIRE

Figure 1. SSDL Microsatellite

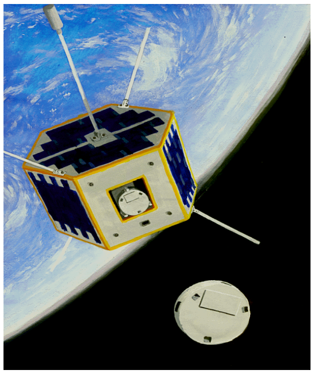
SAPPHIRE Satellite

The first satellite designed by SSDL is SAPPHIRE [11]. SAPPHIRE's mission will be to test the space worthiness of some special infrared MEMs sensors designed at the Jet Propulsion Laboratories (JPL) in Pasadena, CA and provided by Professor Thomas Kenny of the Mechanical Engineering Department at Stanford University. Also on board SAPPHIRE are a black and white digital camera and a voice synthesizer capable of broadcasting typed messages to Earth over amateur radio frequencies. The concept and completed SAPPHIRE are shown in Figure 1. SAPPHIRE is ready for launch at the writing of this paper, but a low-cost (< $50K) has not been obtained.

OPAL Satellite

The second SSDL satellite called OPAL [12] is nearing completion with a scheduled launch of September 1999 on the Minotaur launch vehicle from the commercial launch facilities at Vandenberg AFB, CA.

The OPAL's primary purpose is to launch Picosats. An OPAL Picosat [13] is a fully operational science craft 3" x 3" x 1" in size. Figure 2 shows an artist's conception with round Picosats.



OPAL (Tillier)

Figure 2. SSDL Microsatellites

At least four of the Picosats will be launched from OPAL. Undergraduate students from Santa Clara University in Santa Clara, CA are building one Picosat. The second is being built by a small group of amateur radio satellite operators in the San Francisco area. The remaining two are being provided by the combined efforts of The Aerospace Corporation in Los Angeles and the University of California at Los Angeles. OPAL is also space-qualifying a magnetometer and set of commercial accelerometers.

The students that have gained experience in the development of SQUIRT type satellites are now combining their efforts with the students working on formation flying to form the core of the Orion design team.

Formation Flying Testbeds

Two testbeds were developed at Stanford to demonstrate the basic GPS sensing and control issues for formation flying. The first uses three fully autonomous vehicles (Figure 3) that free-float on a granite table. The vehicles use onboard GPS sensors with four antennas and an indoor GPS Pseudolite environment [2]. These vehicles have been used to study estimation and control architectures for multi-vehicle formation flying. They have demonstrated cm-level station keeping accuracies.

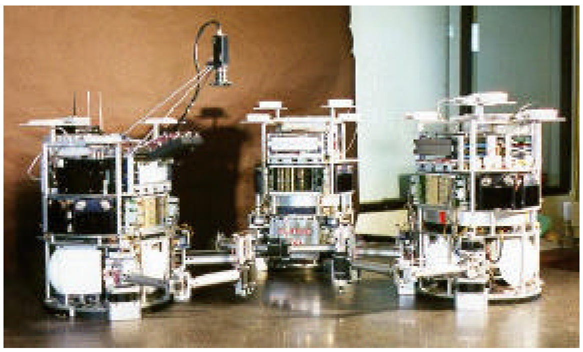


Figure 3. Free-flying Autonomous Robots

Figure 4 shows the second testbed which was developed using lighter-than-air vehicles (blimps) to demonstrate that Carrier-phase Differential GPS (CDGPS) can be used to accurately sense and control a cluster of vehicles that undergo general 3D motion.

Figure 4. Free-Flying Blimp

The research to date on the second testbed has concentrated on developing the GPS algorithms necessary to determine the relative position and attitude between multiple vehicles that can undergo general 3D motions with relatively large separations. These new algorithms will be used to demonstrate robust formation initialization and maintenance on the new 3D testbed.

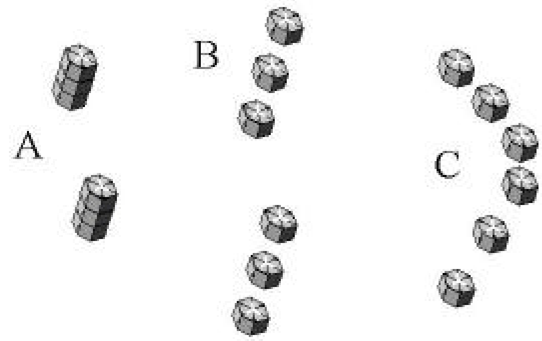


Figure 5. Three basic phases of the Orion Mission

ORION Mission Overview

The objective of the Orion mission is to demonstrate several key sensing and autonomous control technologies that are necessary to develop a virtual spacecraft bus. This will be accomplished using a distributed array of simple, but highly coordinated micro-satellites designed and built in-house. As illustrated in Figure 5, the current plan is to use a constellation of six Orion satellites to demonstrate the relative ranging techniques. These satellites will be launched and deployed in one or two stacked set (A). This configuration will be used to perform an initial reference calibration for the GPS receivers. The next step will be to split the stacks and perform coarse station keeping of the micro-satellites within each trio (B) (possible scenario: 1-km separation with tolerances of approximately 100 m). The vehicles will be controlled within an error box and 3-axis stabilized using feedback from the onboard GPS receiver. When we have determined that the six satellites are functioning properly, the two groups will be combined into a single coarse formation. The next phase (C) will be used to perform precise station keeping maneuvers for periods of approximately 1/2 an orbit (possible scenario: 100 m along track vehicle separation controlled to approximately +/-5 m tolerance along-track and radial). The real-time relative separation and attitude measurements will be validated using onboard crosschecks between the six vehicles.

A simple digital camera will be used to verify the pointing accuracy within the formation. More sophisticated real-time validation techniques, such as laser ranging, will be included as permitted by the power and mass budgets. The primary means of validating the real-time measurements will be to store and then downlink the raw carrier phase and pseudo-range data. Measurements will be taken on-orbit while selected ground stations have the same GPS constellation in view. Downlinked data will then be post-processed to validate the real-time measurements using techniques already demonstrated on the JPL TOPEX mission.

During all phases of the mission, the commands from the ground will specify maneuvers for the entire formation. Each satellite will then independently calculate the maneuvering commands required performing relative separation and rendezvous operations. The onboard GPS receivers will serve as the primary means of orbit and attitude determination.

Other, more traditional sensors will be included if possible under the power and mass budgets. However, the concept described above should provide the lowest cost, lowest risk approach to demonstrate these vital technologies.

The Orion Microsatellite

The Orion Spacecraft is being designed to support a technology demonstration of precision constellation formation flying using GPS for the primary relative-position determination. One of the major design goals of the spacecraft bus development is to use commercial-of-the-shelf parts to keep the cost low while still achieving a 6-12 month operational life.

Orion Spacecraft Design Philosophy

Low-cost, low-power, minimum size, lightest weight, short lead time on parts, maximum performance, short (6-12 months) operational life time, and low-cost – these are the parameters being used by students to design the Orion spacecraft. The low-cost being is emphasized twice to indicate its importance. The short operational lifetime not only is emphasized for low-cost, but to meet the rapid development cycle required to develop technology faster.

To perform the requirements of 3-axes stabilization, station keeping, being built by university students and at university facilities, different trade-off parameters are used than in the normal aerospace development design. In addition to the development, building and testing of these Orion spacecraft, five of the six final spacecraft to perform the Orion Mission will be built at other universities.

Orion Operational Testing Timeline

Prototype mockups of the Orion spacecraft will be tested in facilities used for the Free-Flying Blimps in Figure 4. The first engineering model of the Orion spacecraft is expected to be complete in late 1998 and (Orion I) a single flight model for launch in late 2000 or early 2001. Five other universities will be selected in mid 2000 to participation in the construction of Orion I. Stanford University and five other universities will build Orion II – Orion VII for formation flight demonstration in 2002.

Stanford University expects to participate in the Nanosat Program as part of the TechSat1[17] program. This program has a launch in late 2000 and some of the Orion spacecraft components may be flown as test components on these nanosatellites.

Designing Orion I

To meet the mission goals, the microsatellites will need both attitude control and station keeping ability. For autonomous operation, a high-performance inter-satellite communications system would also be required. The major effort to date has focused on determining the general requirements for:

1. Size, weight and power capability of the bus structure,
2. Candidate C&DH processors,
3. Station keeping hardware,
4. Attitude control system hardware,
5. Inter-satellite communications, and
6. Inter-subsystem communications.

These characteristics represent new additions (or major changes) to the previous SSDL SQUIRT designs, examples of that are shown in Figures 1 and 2.

Shape, size, weight and power

A cube was chosen as the basic shape of the bus structure for optimum utilization of the surface area and the internal volume. The initial size was chosen as a 0.5 m cube. This size spacecraft would produce about 30 W average power (assumes the spacecraft has attitude control, 16% efficient body mounted solar cells, is in a LEO orbit with a 35% eclipse time). This 30 W average was chosen as the maximum power budget for continuous operation, knowing that GaAs solar cells with up to 21% efficiency could be added later. The design effort is to use less than 30 W such that lower cost Si cells could be used.

An initial target weight of 40 kg was selected based on the estimate of the components required. Previous experience from the SSDL SQUIRT program indicated that the structure should be fabricated from honeycomb sheets with a stacked tray arrangement. This method reduces the use of costly, precision and intricate CNC machined parts. The approach is also modular, which is essential for a rapid prototyping development.

Candidate C&DH processors

Space rated processors are not feasible for this mission as they are typically too expensive and require too much power. The Intel 386 radiation hardened processors and versions of the PowerPC were initially evaluated for size, processor speed, availability on commercial single board computer (SBC), power consumption and support software. However, most of these computers are not available in low power versions on SBCs.

To maintain compatibility with ongoing development efforts at the Goddard Space Flight Center the *StrongARM*™ processor was selected as the baseline C&DH computer for this mission. The important advantages of this computer are that it is available in several versions, it offers very high processing speed, and has a low power consumption. The StrongARM has another advantage in that a version of the Linux operating system is available for it. The high level of current industrial interest in this computer strongly suggests that SBC's will be available for Orion. The current plan is to use a modified version of the *AutoCon*™ flight control software, which was developed by NASA GSFC to perform autonomous control on E0-1 [1]. The AutoCon control architecture uses an innovative mix of fuzzy logic and natural language to resolve multiple conflicting constraints and autonomously plan, execute, and calibrate routine spacecraft orbit maneuvers. A development StrongARM computer board will be used to evaluate the AutoCon flight control software for the Orion mission.

Station keeping hardware

There are several types of thruster systems that can provide the station-keeping for Orion. However, for simplicity, we did not consider mono- or bi-propellant systems that use highly reactive liquids or gases. These thrusters pose a serious danger, and cannot realistically be designed by students.

A non-volatile compressed gas (Nitrogen) system was chosen for Orion. The design followed two recent examples on the NASA Safer system and AERCam under development at JSC. The tank volume and pressures are being determined with a propulsion simulation that allows a trade study of the various mission scenarios. Commercial valves, nozzles and regulators have been evaluated and some initial valves ordered. Generally, the limiting factor in this selection is the availability of commercial small, low-power valves.

Several issues will have to be addressed during the development of the station keeping subsystem, including the system simplicity, the mission lifetime and requirements, the power required, and the cost. Simplicity is key if the system is to be developed in-house. To satisfy the power issue, low-power vacuum rated valves will be investigated. Mission lifetime requirements will be addressed by selecting the nozzle size and maximizing the fuel storage. To avoid developing a very high-pressure fuel storage tank, the current baseline is to use manned-flight-qualified storage and high-pressure systems similar to those on SAFER and AERCam. This high-pressure device will then be connected to a low-pressure system built by SSDL.

The thruster system will also have a micro-controller that receives high-level commands such as the thrust vector, level, and duration from the C&DH, and then activates the appropriate valves. This decoupling between the thruster system from the rest of satellite is aimed to accelerate the development process. To perform the station keeping, the baseline plan is to use 0.05 N thrusters. This thrust level can be scaled to trade-off mission life with maneuvering time. Work continues on evaluating this trade-off using the linearized relative orbital dynamics (Hill's equations). Further work is required to finalize this analysis, but the current studies indicate that 6 kg of fuel will provide a useful mission life of 4-6 months.

Attitude control system hardware

A zero bias momentum wheel or three reaction control wheels will be required to perform the attitude control. Note that these wheels are typically not available for space missions for less than $100K per device. Thus, the current plan for Orion is to use vacuum rated, brushless DC motors to build our own reaction wheels.

For the baseline satellite (mass 40 kg, 0.5m cube) in a 500-600 km altitude orbit, the Earth magnetic field derives external torque of 10^{-5} N-m for a residual dipole of 1 Amp-m2 which is 10 times and 100 times stronger than aerodynamic and solar torque, respectively. If we assume the maximum slew rate as 2 degree/sec, the corresponding maneuvering torque is $3x10^{-3}$ N-m. Adding a safety factor to account for the uncertainty in the mass distribution of the satellite, the torque of a motor in the reaction wheel system should be approximately $5x10^{-3}$ N-m. If the wheel dumps angular momentum three times a day, the amount of momentum storage should then be approximately 0.1 N-m-sec. These specifications can be achieved using a very small flywheel with a moment of inertia of $2.2x10^{-4}$ kg-m^2 combined with a 5000 RPM motor. The momentum of the wheels will be dumped using torquing coils.

Inter-satellite communications

The main requirement for this subsystem is to provide communications between the spacecraft in the constellation. Again, many commercial systems can be used to link computers in a network without being physically connected. Wireless Ethernet is an ideal choice, since it can support the high data rates required. This solution would also take advantage of spread-spectrum technology. Because the transmitter power will most likely be under 1 W, we will not have to obtain FCC approval to use it in space.

The Lucent Technologies WaveLAN PCMCIA wireless Ethernet card looks promising for Orion because it fits into a PC card slot that is standard on all current model laptop computers, and it also exists on the StrongARM evaluation board. Another reason for the WaveLAN is the availability of source code, and wide operating system support.

Inter-subsystem communications

In designing the inter-subsystem communication bus, the objective was to develop a system that meets the high performance needs of Orion, but is flexible enough to be used on future SQUIRTs. An additional objective was to reduce the number of wires required and to allow subsystems to be easily added or removed. These goals narrowed the choices to synchronous serial designs, which allow fast data transfer over only 2 or 3 wires.

Among the industry standard protocols, the Serial Peripheral Interface (SPI) was attractive for its simplicity and wide device support, but requires an external address bus, which limits the number of subsystems for a given number of address lines. To allow for more expansion without adding more lines, one address will be reserved for communication using the Inter Integrated Circuit (I2C) protocol, which sends addresses over the data lines. Adding the explicit ability for multiple devices to initiate SPI, communications (Multi-mastering) provided a protocol that meets or exceeds all of our requirements, the SPI-MM/I2C. With 4 address lines, 2 data lines, ground, and an additional handshaking line everything fits in a DB9 connector.

Summary

The emphasis of this initial work has been to investigate the various alternatives for the main subsystems of the satellite. The main result is a set of trade off that can be analyzed to compare the important features, namely performance and power. The final decisions for each subsystem will be made as the mission development proceeds. However, these initial studies indicate that the desired Orion mission can be achieved using micro-satellites that meet the target goals of mass, power, and cost.

Conclusions

This paper has outlined a new GPS based formation flying mission called Orion. Using a fleet of six low-cost micro-satellites designed in-house, Orion will investigate a variety of GPS sensing and autonomous control related issues. A successful Orion mission will complete an essential step towards formation flying and virtual platform capabilities on future Earth Science Enterprise missions.

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