The Bitsy™ Spacecraft Kernel: Reducing Nanosatellite Mission Cost in the MSFC Future-X Program Through Miniaturized Technologies

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Introduction

A team led by AeroAstro Incorporated was selected under the Future-X program to fly an experiment in late 2000 to demonstrate key elements of reducing space mission cost utilizing Bitsy™ Spacecraft Kernel technology. The Small Payload Access to Space Experiment (SPASE) is funded through the Future-X program, and is to be launched in late 2000 using the Space Shuttle. The mission will also carry a small microgravity payload.

The entire first mission, including space and ground systems and launch interfaces, will cost under $2M. The recurring cost for follow-on microgravity spacecraft will be under $1M. Achieving on-orbit science missions with a cost comparable or below that of suborbital flights is made possible by:

- Creation of a *standardized core of spacecraft capabilities*, not a standard bus, based on commercial-off-the-shelf (COTS) technologies, which the science team uses to manage spacecraft functions (patent pending);

- Miniaturization, which both reduces recurring costs (fabrication and parts) and makes a minimal demand on launch vehicle services with very high reliability.

The spacecraft "kernel", as opposed to bus, does not have a traditional division into discrete subsystems, but rather manages power, thermal control, ACDS, C&DH, and communications in a package of a few kilograms. Its small size, light weight, and unique extensible architecture enables a variety of customizations to be added as needed to greatly expand the range of achievable missions. These added capabilities include modest in-space propulsion, which enables missions including those requiring large ΔV for spacecraft inspection, orbit initialization or station keeping, or achieving unusual or energetic orbits without requiring very expensive launch capability. While Bitsy™ technology enables flying significant science, communications, and remote sensing missions with total mass of 10-60 kg for

costs similar to suborbital flights, there is in principle no limit to the size or complexity of payloads it can accommodate.

The spacecraft program currently underway will demonstrate the capabilities provided by the combination of miniaturization and nanospacecraft architectures. It will perform a flight demonstration of the spacecraft, ground station, and flight operations control software offering standard interfaces to payloads and to launch systems, to be launched in late 2000 on the Shuttle Hitchhiker accommodation. The Bitsy™ kernel concept, progress to date on the SPASE mission, and the fundamental design and architecture decisions for each will be discussed in this paper.

The Future-X Mission (Bitsy-SX/SPASE)

The goal of the NASA Future-X program is to reduce the cost of access to space. While their focus is on launch vehicle technology, they funded the SPASE satellite program in recognition of the fact that "access to space" encompasses the entire mission process, including satellite creation, launch, and orbital operations. A pathfinder program of this type is then essential in reducing the total real cost of access to space.

Future-X, managed out of Marshall Space Flight Center, is funding AeroAstro and its subcontractors to produce, launch, and operate the SPASE vehicle. Marshall Space Science Laboratory (SSL) is providing the science experiment and science operations management. The experiment explores protein crystal growth in microgravity: in a sealed and temperature-controlled chamber, crystals are grown, back-illuminated and imaged, melted, and regrown. Since the idea

of Bitsy™ is of a spacecraft kernel which attaches to a vehicle to provide essential functions, the science experiment housing itself will be the primary vehicle structure.

The demonstration technology to be flown is the Bitsy™ Spacecraft Kernel. Proving this architecture will enable significant progress in reducing space mission costs by using the architectures and technologies unique to the growing field of nanosatellites.

The Bitsy™ Kernel Architecture

All spacecraft have substantially the same basic requirements: power, communications, guidance and navigation, and command and data handling. Conventionally, the design of a spacecraft is effected by partitioning the spacecraft into two independent sub-systems: a payload system and a transport system. The payload system comprises the mission-specific equipment, such as a collection system that collects data in a research satellite, a relay system that retransmits signals in a communications satellite, and so on. The transport system, or "bus", comprises the equipment required to effect the mission in space, including: the power generation and storage system, the attitude determination and control system, the command and data handling system, the communications system, and the infra-structure and super-structure to support each of the components of each system.

Although the functional partitioning of tasks between payload and bus provides the desired degree of functional independence for effective system design, the physical constraints inherent in spacecraft design often forces a structural dependence that minimizes the advantages that can be gained

by this functional partitioning. If the mission is to visually collect data related to the earth's surface, for example, the solar panels must be arranged so as not to obscure the view of the earth, and the spacecraft must be controlled to orient the visual collection device toward the earth. Conversely, if the mission is to measure the effects of weightlessness on crystal growth (as in the SPASE mission), the solar panels can be placed anywhere on the exterior of the spacecraft, whereas the spacecraft propulsion and control system must be designed to minimize acceleration in any direction.

These kinds of interactions between the payload and the bus, requiring bus redesigns — often late in the development process, as unexpected issues are encountered in payload development — are often a major contributing factor to the high cost, in time, effort, and material, of conventional spacecraft development programs. Because of the interdependencies imposed between the payload and bus, the re-use of systems or sub-systems among spacecraft having different missions is a sought-after but often unachievable goal.

The Bitsy™ kernel approach, then, is not to attempt to draw the line between bus and payload, but rather between mission-specific and cross-mission or "kernel" functions. Instead of trying to design a generic bus that meets the needs of a wide variety of mission types, Bitsy™ selects the functions that are in common across a variety of mission types and provides them in a single, reliable, standard unit.

Bitsy™ Kernel Design Overview

Bitsy™ is an enabling technology, meaning that one does not fly a Bitsy™ *per se*, but rather uses Bitsy™ as the starting point of the development of a full spacecraft. By using the twin approaches of COTS and standardization to their fullest extent, this kernel offers significant cost and turnaround advantages over traditional bus development.

Standardized Core of COTS Technology

Two primary cost drivers of any engineering product, particularly spaceborne devices, are part costs and integration time. S-class parts and units are prohibitively expensive, by necessity since they are low-production, labor-intensive products themselves. The domino effects of "a few minor changes" on a previously built product, where long hours are spent in integration trying to get the system to work together as a whole again, are well known to all who have worked on such a project. These are the issues AeroAstro addresses in Bitsy™ through the use of a standardized core of COTS technologies.

COTS, in this context, is more literally meant than usual in the aerospace business. By "commercial", true commercial suppliers are intended — electronics one can order from DigiKey, D-style connectors that might otherwise have been found on the back of a personal computer, radios with a history of ruggedness but which have not before been attempted in space because of the absence of an explicit MIL-STD-883 rating. By "off-the-shelf", products with a more immediate, consumer-product level turnaround are preferred — with a delivery time measured in days or weeks, not months or years.

While the use of this level of COTS components addresses the part cost issue, the "standardized core" addresses the runaway integration times that turn each spacecraft bus production into an individual development project. Each Bitsy™ model will have a well-defined set of capabilities and a well-defined means of interface — a "solution space" of missions for which that model can be effectively employed. The performance of Bitsy™ within that solution space will be extremely well-tested, understood, and reliable. The mindset of the customer is then to pick the model of Bitsy™ which will provide the power, communications, and C&DH performance required, and build from there; not the other way around, where the customer comes to the bus supplier with a set of requirements that does not quite fit any device the supplier has, and as a result the bus supplier takes a working device and makes "a few minor changes".

In order to make the solution space as large as reasonable and therefore serve a significant number of missions, the capabilities of a given model of Bitsy™ must be broad from the outset. The power system must be capable of handling (for example) supplies and loads from 0 to 100 Watts, with between 0 and 16 individual solar panel strings, 0 to 200 Watt-hours of Lithium-ion secondary batteries, and 0 to 700 Watt-hours of Lithium-Thionyl-Chloride primary batteries, delivering individual switched circuits that can supply 0 to 30 Watts each. These capabilities are designed in from the beginning, tested, and established as part of the standard core of a particular Bitsy™ model.

An analogy here is to the purchase of a car. One does not approach the auto dealer with requirements for cylinder bore and stroke, acceleration performance, and seat dimensions; the auto manufacturer makes models of car with various engines and abilities, and includes adjustable seats: the customer chooses from among these well-tested production-line units. The dealer offers options, air conditioning or a better stereo or a service plan, which the dealer is confident is either a known and tested addition to the vehicle, or will not affect its production.

The final note of standardization here is standardized interfaces. The Bitsy™ kernel will always have to interact with unique, new, mission-specific items. In order to retain the advantages of standardization and reliability, then, these interactions must be through well-documented and well-understood interfaces: bolt hole patterns, power supplies, and data throughput will all be standardized. Simple data interface is through analog and digital discretes; basic information exchange is through RS-232/422/485; and more complex missions requiring more complex buses, such as 1553/1773, CAN, or FireWire, would be supported in future models of Bitsy™.

The Application of a Spacecraft Kernel

The Bitsy™ model being developed for the Future-X SPASE mission is the most basic version: the Bitsy™-SX. It communicates at an average of 9600 baud from LEO to a very moderate-gain ground antenna, supports power consumptions up to at least 50 Watts and power supplies from solar panels and/or Lithium-Ion rechargeable batteries and/or Lithium-Thionyl-Chloride one-time batteries,

uses RS-232 in addition to analog and digital discretes to communicate with the payload, and supports simple timed commanding (turn this device on at time T1, send these bytes at time T2, and so forth). It monitors telemetry and performs a specified action when an input value crosses a threshold — the most basic type of housekeeping, but still sufficient to perform thermal control and simple ACS.

SPASE will use Bitsy™-SX on an octagonal spacecraft that fits inside a Shuttle GAScan, with the spacecraft covered in solar panels and carrying 7 Watt-hours of Lithium-Ion batteries; net orbital average power is near 5 Watts. ACS is passive, using hysteresis rods and permanent magnets to keep the vehicle body rates below 10^{-5}g for the crystal growth experiment. The payload interaction consists primarily of keeping the crystal growth cavity within a specified temperature range, commanding a digital camera to take images periodically, and downloading those images when a ground station contact occurs. These requirements, then, are well within the Bitsy™-SX solution space; other missions can then use Bitsy™-SX, with no modifications to Bitsy™ itself, only the addition of mission-specific elements which act through the standard interfaces.

The AeroAstro Small Payload ORbit Transfer vehicle, or SPORT, is a new approach to getting spacecraft to Low-Earth Orbit. There are many inexpensive secondary launch opportunities, particularly on Ariane; but they are to GTO. There are many spacecraft whose small size and low cost can take advantage of secondary launch slots; but they need to go to LEO. SPORT is a transfer vehicle that uses a combination of propulsion maneuvers and aerobraking to bridge the gap between these two. And

SPORT uses a Bitsy™-SX. It uses Lithium-Thionyl-Chloride primary batteries instead of solar panels and rechargeables; it is a spinning vehicle which uses Bitsy™'s sense-and-threshold function to govern an analog ACS; it has no RS-232 devices, but a number of valves, heaters, and regulators that use Bitsy™'s analog and digital discrete channels. Since the development of SPORT can focus on only the SPORT-specific issues — propulsion and related ACS, the amount of energy needed in the primary batteries, the satellite carrier structure — and treat power regulation and switching, communications, and monitoring / control functions as "solved problems", the development of SPORT is that much faster, cheaper, and more reliable.

KITComm pty. of Australia commissioned AeroAstro to do an initial design of a constellation of spacecraft to perform remote asset tracking. AeroAstro designed a bent-pipe system that offered near-real-time communications with all assets within thousands of kilometers of each ground station, placing system complexity (and therefore upgradeability) on the ground instead of in the spacecraft. This spacecraft also was designed around a Bitsy™-SX. It used body-covering solar panels and Lithium-Ion batteries, like SPASE, but is a spinner, like SPORT. The payload was a radio repeater, which required only simple monitoring and power control. The KITComm spacecraft required much more power than either SPASE or SPORT, but still well within Bitsy™-SX's capabilities. Bitsy™-SX could thus be used unchanged for the KITComm constellation as well.

AeroAstro recently completed a study for NASA's New Millennium Program, studying the spacecraft bus portion of the Disturbance Reduction System spacecraft currently under

consideration by the New Millennium Program for ST-5 (DS-5). This vehicle requires significantly greater capabilities than Bitsy™-SX, hence calling for a different model of Bitsy™. In keeping with the kernel concept, however, this new model of Bitsy™ would be given a sufficiently broad solution space beyond the DRS mission to be usable, without modification, in other spacecraft of similar scale. It would have a low-power commercial microprocessor on-board, with 16 Megabytes of memory, 32 independent RS-422 channels for communication with mission-specific subsystems and devices, a 300 Watt capable power system, up to 20 Watts EIRP out of the radio, and commensurately greater numbers of discrete inputs and outputs. Note that the intended ultimate cost and time savings here comes from not trying to stretch Bitsy™-SX to work with the DRS mission, but recognizing that a new Bitsy™ model serving a new solution space is called for.

Miniaturized Technologies

One fundamental fact of spaceflight is that mass is money. The smaller, lighter, and more compact a vehicle (and hence its parts) can be, the more launch opportunities become available, and the lower the cost. It is therefore a priority of the Bitsy™ product line to be as miniaturized as possible while still offering the cost savings of COTS parts and standardized capabilities and interfaces.

Technology Goals and Priorities

The technology development efforts at AeroAstro to advance the Bitsy™ product line are twofold: technologies that advance the Bitsy™ core itself; and technologies which use Bitsy™'s standard interfaces to create an extended product that is more immediately useful to a class of customers. Bitsy™ core technology developments include

♦ Industrial-grade microprocessors and embedded controller units which can be used in space, including the extensibility (PC/104, compactPCI, ISA) that this implies
♦ Information transfer protocols applicable to spacecraft, making not only communication but actual information exchange among spacecraft devices standard
♦ Batteries with ever higher power density and longer lifetime
♦ High-efficiency power regulators and DC-DC converters
♦ MMIC devices offering an entire radio system on one or two integrated circuits

Bitsy™ extension technologies include

♦ High-efficiency solar arrays, including multijunction, multispectral, and other cell technologies
♦ Deployable, articulated, and inflatable devices, so that a spacecraft which is compact on launch is not handicapped by its small surface area on orbit
♦ Smaller and less expensive launch vehicle mating systems than are currently used, including multi-spacecraft deployment mechanisms
♦ Nanospacecraft propulsion which provides the low minimum impulse bit required to control very small spacecraft

Each of these items has been researched to some extent by AeroAstro in the interest of

advancing the Bitsy™ product line. Some highlights include

♦ Space-ready Lithium-Ion and Lithium-Thionyl-Chloride battery systems, including recharging circuitry and structures highly resilient to physical and thermal shocks, developed for and delivered to the Air Force for rigorous testing

♦ Vaporizing-liquid propulsion units, also for the Air Force, built and tested to demonstrate their compact size, high degree of controllability, and inherent safety

♦ A miniaturized, low-power X-band radio system, described in detail in the next section.

Miniaturized, Low-Power X-band Transponder

AeroAstro's most recent kernel technology development effort has produced a design and a production plan for an X-band spacecraft transponder weighing only 150g, consuming under 8W, and fitting on miniature PC boards in a space less than 5x5x7.5cm. It produces 2W EIRP and supports up to 750kbps downlink with CCSDS formatting. This level of miniaturization and power efficiency is far beyond anything available on the market today. The transponder is designed to proceed smoothly from this mini-PC-board product to even further miniaturization and power reduction by employing hybrid construction, followed by ASIC development, followed by Low-Temperature Cofired Ceramic (LTCC) production.

AeroAstro chose communications systems as our next step in technology development in

recognition of a lack of comparable products in the commercial marketplace. Although there has been a strong recent push toward reducing spacecraft mass and cost, there is no commercially available communications equipment that will significantly contribute to that reduction. While spacecraft mass has dropped over an order of magnitude in the past ten years, radios have not followed this trend. Since there was no COTS solution available to meet the needs of true nanosatellites, and the COTS solutions for the Bitsy™ product line were sub-optimal at high data rates, AeroAstro is developing the solution itself.

While this miniature X-band radio will be offered for sale as an independent unit, it will also be incorporated into the Bitsy™ product line, and thus be presented to the user simply as a capability of Bitsy™ — with the internal details transparent to the user. However, by reducing the radio size and mass so drastically from existing solutions, the Bitsy™ kernel itself will drop in size and mass, making spacecraft built from Bitsy™ that much more lighter and more compact — and therefore less expensive to fly.

Long-term Bitsy™ Kernel Line

The Bitsy™ product series is expanding to offer increased flexibility. There are customers with specific kernel requirements that cannot be served by the Bitsy™ models available, and for them AeroAstro is developing a series of advanced products with increased capabilities such as higher processing power, precise pointing, and extremely capable on-orbit maneuvering. Many customers require a full bus in the traditional sense, with mission-specific bus functions such as solar panels and ACS

actuators and the like, who will be served by custom buses based on standard Bitsy™ kernels. However, many customers require a spacecraft very similar to one that has already flown, to perform a very similar mission. These can now be served for very low cost by customizing to their specific mission needs using fully developed Bitsy™-based standard spacecraft kernels.

Some mission-specific Bitsy™ Spacecraft Kernel products that AeroAstro is developing are:

♦ Microgravity research vessels — the SPASE vehicle
♦ Product demonstration vehicles, where a star tracker, IMU, small thruster, radio, solar panel, deployable structure, or any other individual device which fits in a certain envelope can be flight-tested on a Bitsy™-based nanosatellite
♦ Radio relay constellations, such as KITComm or similar venture in which there is much interest today
♦ Sensor constellations, where a fleet of Bitsy™-based nanospacecraft carrying the same sensor suite fly through an interesting region of space

Every custom bus AeroAstro builds will also be designed with an eye toward reuse within that mission type.

The First Bitsy™ Mission: SPASE Program Overview

The first Bitsy™ will fly on the SPASE vehicle in late 2000. Future productions of the Bitsy™-SX kernel are planned to take 6 months after receipt of order, with the schedule driven by long-lead acquisitions; hence the priority for locating or developing faster-turnaround products.

Bitsy™-SX will be mated with the Marshall Space Sciences Lab Microgravity Crystal Growth Demonstration at Marshall Space Flight Center. The integrated unit will be functionally and environmentally tested, and delivered to the Hitchhiker office for integration onto Shuttle. Shuttle integration is of course a concern, which has been allotted for in the budget, although AeroAstro and the Future-X office hope that SPASE will be a pathfinder for establishing more straightforward integration methods for small, simple satellites.

The SPASE vehicle will be deployed from a GAScan at an altitude high enough above the atmosphere to remain under the 10^{-5}g requirement for the science experiment. There is no electrical connection between the SPASE vehicle and the Shuttle, and no requirement for Shuttle crew attention beyond the deployment of the satellite.

Communications with the spacecraft will be conducted from the University of Alabama at Huntsville, offering an educational outreach benefit to the program where students will be directly (not tangentially) involved in the actual operations of the vehicle. The SSL science team will establish the operations for the crystal growth experiment, which will produce information on microgravity crystal growth that has not been acquired before, and which does not require the costly return of the sample to Earth. The science mission is designed to last 6 months, with operations after that being an opportunity to test the duration limits of the technologies on-board.

Conclusion

Bitsy™-SX is the first of a line of spacecraft "kernel" modules offered by AeroAstro. By delivering a standard, consistent, reliable spacecraft kernel, or core module, AeroAstro will reduce the cost and the turnaround time for future space missions because a core of spacecraft functions can be built into a low-cost, customizable, extensible "kernel" product. The SPASE mission, in addition to performing valuable microgravity science, will demonstrate the applicability and benefits of the spacecraft kernel approach for single and multiple nanospacecraft.