Small Rocket/Spacecraft Technology (SMART) Platform

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ABSTRACT

The NASA Goddard Space Flight Center (GSFC) and the Department of Defense Operationally Responsive Space (ORS) Office are exercising a multi-year collaborative agreement focused on a redefinition of the way space missions are designed and implemented. A much faster, leaner and effective approach to space flight requires the concerted effort of a multi-agency team tasked with developing the building blocks, both programmatically and technologically, to ultimately achieve flights within 7-days from mission call-up. For NASA, rapid mission implementations represent an opportunity to find creative ways for reducing mission life-cycle times with the resulting savings in cost. This in turn enables a class of missions catering to a broader audience of science participants, from universities to private and national laboratory researchers. To that end, the SMART micro-spacecraft prototype demonstrates an advanced avionics system with integrated GPS capability, high-speed plug-and-play-able interfaces, legacy interfaces, inertial navigation, a modular reconfigurable structure, tunable thermal technology, and a number of instruments for environmental and optical sensing. Although SMART was first launched inside a sounding rocket, it is designed as a free-flyer.

INTRODUCTION

For several decades now, NASA has been experimenting and implementing multi-use modular systems. From the Multi-Mission Modular Spacecraft (MMS) of the 1970s and 80s, to the Small Explorer Program (SMEX) "production line" spacecraft of the 1990s, a common theme of streamline missions has been postulated with relative good success. As of recent, there have been several instantiations of "standard" spacecraft both in concept and flight. Achieving multi-use, while preserving flexibility is however, a different story, and one the Small Rocket/Spacecraft Technology (SMART) platform is in the process of writing. A new architecture that incorporates best practices of the past, and folds new technology advances into a more progressive approach to multi-purpose spacecraft has already been described in a couple of publications [1,2]. Now the NASA Goddard Space Flight Center (GSFC) and the Department of Defense Operationally Responsive Space (ORS) Office are exercising a multi-year collaborative agreement focused on a redefinition of the way space missions are designed and implemented. A much faster, leaner and effective approach to space flight requires the concerted effort of a multi-agency team tasked with developing the building blocks, both programmatically and technologically, to ultimately achieve flights within 7-days from mission call-up. For NASA, rapid mission implementations represent an opportunity to find creative ways for reducing mission life-cycle times with the resulting savings in cost. This in turn enables a class of missions catering to a broader audience of science participants, from universities to private and national laboratory researchers. To that end, the SMART micro-spacecraft prototype is expected to launch from the Wallops Flight Facility on a Terrier Orion Sounding Rocket in June 9th of 2011. It demonstrates an advanced avionics system with integrated GPS capability, high-speed plug-and-play-able interfaces, legacy interfaces, inertial navigation, a modular reconfigurable structure, tunable thermal technology, and a number of instruments for environmental and optical sensing. Although SMART first launches inside a sounding rocket, it is designed as a free-flyer. After its debut suborbital flight, it will be about 60-70% ready for orbital operations: a small step forward, but a judicious application of technology for a leap ahead.

SMART OBJECTIVES AND TOP-LEVEL REQUIREMENTS

SMART broadly supports a Modular Open Systems Architecture (MOSA), and the development of

technologies for launch vehicle and launch Range, and spacecraft applications. SMART also represents a system instantiation (point design) following the MR²/MARS architecture defined in the References [1,2]. In fact, the system is designed to provide faster, less expensive access to space because of its modular, reconfigurable design, yet without compromise in flexibility (or creativity) that can affect "standard systems". As an exercise in flexible, multi-use systems, users can adapt SMART to fulfill a variety of missions ranging from optical imaging to radio-frequency applications, and even as test-bed for NASA as an entry vehicle for planetary missions. Specifically for its first flight, SMART's top-level requirements were to:

(1) *Build a miniaturized high-performance, power-efficient processing avionics with built-in plug-and-play-able (PnP) interfaces for small expendable launch vehicles, and small orbiting spacecraft.* The architecture accommodates reconfigurable electronics, and broad commercial radiation hard and/or tolerant components. For redundancy, the processor board includes 2-core processors. High-speed interfaces are also implemented (Gigabit Ethernet and SATA II), and components/sensors attached for their validation (redundant video cameras and redundant Solid State Drives). Legacy RS422 interfaces are also present and exercised (video camera). As the avionics unit were to be tested as well for its capability to host an Automated Flight Safety System (AFSS), a critical NASA and ORS launch Range software technology, a GPS, an IMU, and a Low-Cost TDRSS Transmitter (LCT2) were all added late in the project (the LCT2 operates on a direct-to-ground transmit mode for this flight).

(2) *Build and Flight-Qualify a modular, reconfigurable spacecraft prototype structure*, capable of hosting the avionics and system components of a full-sized micro-satellite. To this effect the system was designed to be as self-contained as possible, even as it resides within a sounding rocket skin. As an added "bonus", the structure also incorporates an Electro Hydro Dynamic tunable thermal plate technology (multi-functional "plate") for heat transfer and thermal test.

(3) *Obtain flight test performance data* of all SMART subsystems, including the SpaceCube avionics and its interfaces, plus thermal plate technology. Flight environment data (axial/radial loads, thermal, vibration, and pressure), and optical data (of deceleration system) are also collected as a way of validating entry probe sensors and actuators and their operation.

SYSTEM DESCRIPTION

As a low-cost "class-D" micro-satellite prototype, SMART has a mix of heritage and ruggedized COTS components chosen judiciously and tested extensively. For mission durations lasting up to a year (more is possible), the current system can prove adequate, given its limitations and constraints.

There are four main components within SMART: The SpaceCube avionics, the reconfigurable structure, instrument sensors, and the thermal system. The thermal plate experiment will not be described in any detail here however, as it is an instrument of opportunity. A system block diagram is shown in Figure 1. Sensors (including the optical cameras) are used to monitor deployment, temperature, pressure, and acceleration environments, as well as position and inertial attitude. Sensor integration into the avionics provides for an account of the flight. Interface testing and sensor data is essential in assessing the avionics and overall system performance.

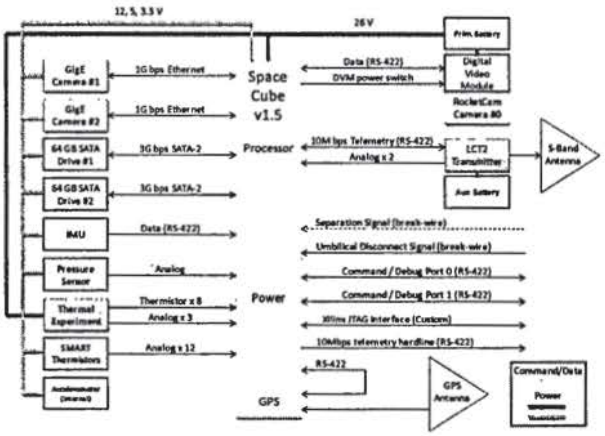


Figure 1: SMART System Block Diagram

The heart of SMART is the SpaceCube v1.5, which provides computing capability to process the large amounts of sensor data, and distributes power to all components except the RocketCam™ and its associated Digital Video Module (DVM). The DVM handles RocketCam™ data, and pipes it through the SpaceCube for downlink and storage. GigE Camera video is processed within the SpaceCube, as are all other sensor data (IMU, GPS, Pressure, and Temperature). The full data set, at a rate of about 3 Gbps, is stored on-board by the redundant 64 GB SATA II Solid State Drives (SSD), and a subset down-linked via the LCT2 S-Band at a rate of 10 Mbps. Because of the large amounts of data generated, real-time display of images will be at a much slower frame rate that the 30 to 90 fps actually stored on-board.

Figure 2 shows SMART's layout. Key components shown will be described in the following sections. Figure 3 illustrates the overall dimensions of the vehicle core, without the Payload Attach Fitting (PAF) cone at the bottom. A photograph of the vehicle during processing is also shown as reference. The volume was constrained by the Terrier Improved Orion sounding rocket, with a bulbous 43.82 cm (17.25 in) diameter skin ("fairing"). The PAF attaches to an 11-inch Planetary Systems Motorized Lightband ™ bolt pattern, and to a ring in the rocket skin. No other attachment to the rocket is used, as to simulate an orbital launch vehicle configuration.

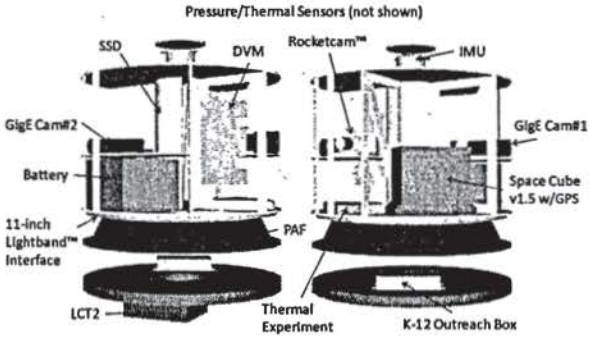


Figure 2: SMART Layout and Component Identification

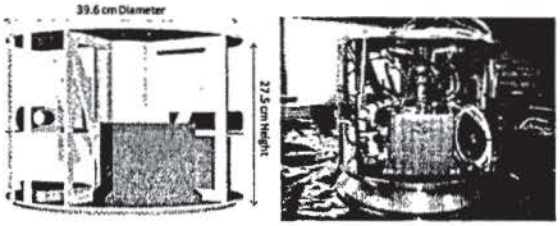


Figure 3: SMART Core System Dimensions

SpaceCube v1.5

The SpaceCube V1.5 avionics represent an evolutionary step from the flight qualified SpaceCube system successfully flown during HST's Servicing Mission 4 and on MISSE-7, providing inherent redundancy through multiple processor cores, high computational capability, and low power consumption. The system allows for legacy RS422 as well as Plug-and-Play-capable interfaces. These include Gigabit Ethernet (GigE), and Serial Advanced Technology Attachment (SATA) II, using the 3 Gbps standard. The SpaceCube itself is a small form-factor package, suitable to small launch vehicle and spacecraft applications, yet it services one of the highest performance payloads ever built at NASA GSFC, with respect to data processing rates. Its block diagram and interfaces are shown in Figure 4. A brief synopsis of the SpaceCube family, including various detailed references may be found in the online "Wikipedia" [3].

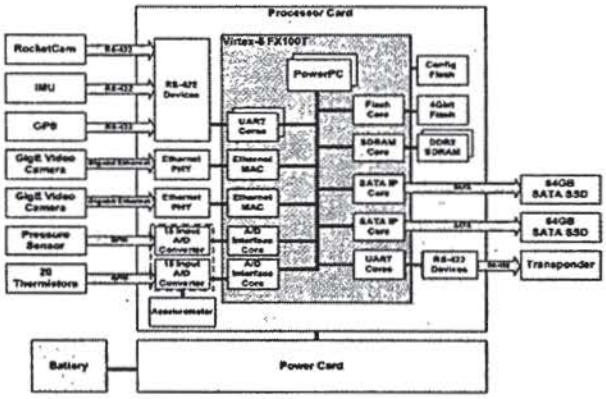
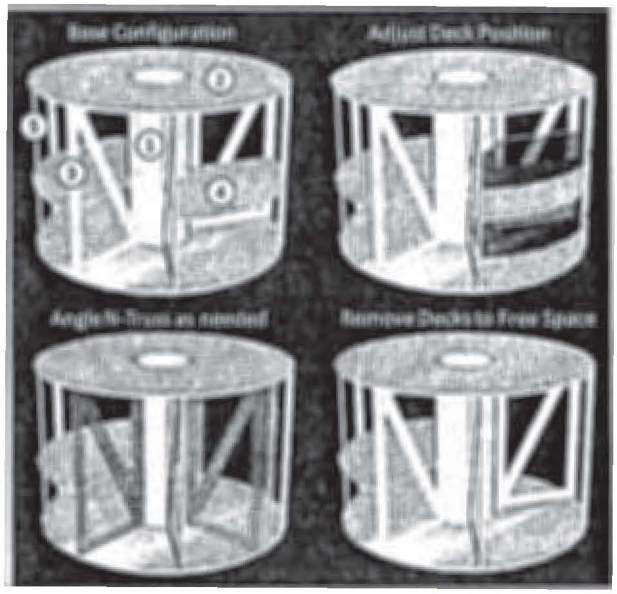


Figure 4: SpaceCube v1.5 Block Diagram

Modular, Reconfigurable Structure

The structure design follows the architectural premises established during MR[2] (Modular, Reconfigurable, Rapid) and MARS (Modular, Adaptive, Reconfigurable Systems) work, beginning in late 2002. From a structure perspective, the objective is to allow for layout changes using some basic components. In this case, "spider" N-truss components with a central thrust tube are arranged within a "spindle" geometry made to fit components that connect either through harness routing along the decks, or though routing within the tube. Mid-decks and top/bottom closing decks, plus vertical longerons complete the design. Simplicity and robustness are the end result. The current layout calls for a circular structure, which provides the most efficient interface to the sounding rocket.

A drawing of the structure is shown in Figure 5, together with reconfiguration options. The internal plates can slide up or down, depending on subsystem volume requirements. The truss structures can also be angled in different ways to accommodate larger boxes if needed, with a corresponding change in internal plate sizes. This design is simple, yet allows for flexibility in adjustments to accommodate subsystems of varying sizes. In addition, complete modules may be stacked-up depending on mission needs, and as allowable. The structural layout is modular and reconfigurable. Two configurations (requiring deck position adjustment) were flight validated to the rather demanding launch environments found in typical sounding rocket vehicles. In fact, during layout the structure had to be modified to remove a deck and relocate a truss in order to allow more space for the space cube. This was done with minimal impact to the design (as these changes are built-in), and to the project.



Structural Components:
(1) Thrust Tube; (2) Closeout Deck; (3) N-Truss; (4) Mid-Deck; (5) Longeron

Figure 5: Modular, Reconfigurable Structure

Autonomous Flight Safety System (AFSS)

Flight termination of space launch vehicles is done today in the same manner it was done fifty years ago. The vehicle is tracked by precision radar, data is returned to a control room monitored by a Range Safety Officer, and, if necessary, flight termination commands are issued by high-powered transmitters to an onboard receiver. As the vehicle flies down range, additional coverage is required by multiple redundant radars and command transmitters linked together by highly reliable data networks.

Although many components of the flight termination system have been updated by modern technology, the cumbersome infrastructure, often deployed in remote locations or mobile platforms, is the same as it was in the 1960's at inordinate cost to ranges—costs that are passed on to the Missions. Additionally, conventional termination systems are susceptible to weaknesses such as radio frequency interference (RFI) or intentional jamming, and lag time associated with human response. A major concern of range safety is that the uplink is a frequency shared with radars. These radars are important DoD and Homeland Security assets. While coordination is possible during an actual launch, it is not offered during pre-launch tests and coordination failures have led to inability to transmit signals to rockets during flight.

The Autonomous Flight Safety System (AFSS) is being developed as a software system by NASA's Goddard Space Flight Center's Wallops Flight Facility and Kennedy Space Center as a means of replacing all this with a simpler, safer onboard system that is orders of magnitude less expensive. The AFSS project will use global positioning systems (GPS), modern Inertial Measurement Units (IMUs), and flight processors to monitor the progress of the launch vehicle with respect to multiple flight termination criteria and, if necessary, terminate the flight without relying on ground-based assets.

To validate the algorithms and software and to define the concept of operations for eventual use, AFSS has completed three successful developmental flights largely adapting commercial grade hardware to support testing. Figure 6 shows one such test system flown on "shadow-mode" (i.e., offline) on-board a SpaceX Falcon 1 launch vehicle, on March 2007 [4]. Further advancement of the technology however, will require development of a lighter, compact and more robust platform on which to host the software for testing, demonstrations and eventually as a qualified flight termination system. The SMART platform is a promising candidate and with funding from ORS, the NASA AFSS software is being deployed on the SMART flight processors.

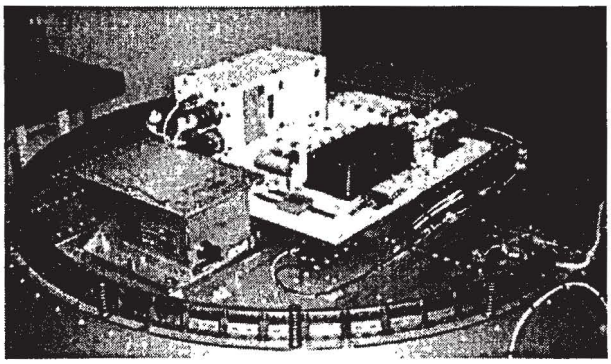


Figure 6: Early AFSS Test Hardware on SpaceX Falcon 1

Low-Cost TDRSS Transmitter (LCT2), and Space-Based Range

The Low Cost Telemetry Transceiver (LCT2) was developed at Wallops Flight Facility to provide a low cost space based range solution for telemetering data. The LCT2 follows the roadmap towards a space-based range with the goal of reducing the operational cost of the range while increasing the response time to the launch industry, the ability to collect data and to ensure range safety.

Originally developed for use with the NASA TDRSS, LCT2 is a fully programmable software based transceiver containing modulator, transmitter, and

receiver subsystems and has been used in a range of TDRSS and non-TDRSS applications to achieve not only satellite communications but direct to ground applications for high bit rate and as a ruggedized test bed for innovative modulation techniques. The modulator is capable of applying various types of modulation schemes to most data rates and formats. The transmitter subsystem RF output frequencies can be scaled to various frequencies and RF power output defined at build time across wide power output levels. The receiver subsystem can be programmed to receive various modulation schemes and bit rates based on customer or mission requirements. Modulation schemes, bit rate settings, RF frequency settings, and power level settings are based on customer and mission requirements and defined at project initiation. Figure 7 shows the LCT2 on-board SMART.

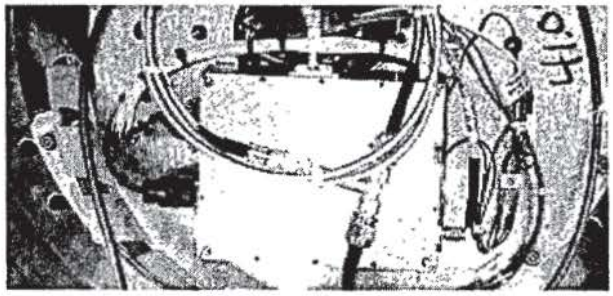


Figure 7: LCT2 on SMART's Rear Bulkhead

On-Board Sensors

SMART has three video cameras on-board: an Ecliptic Enterprises RocketCam™ Video Camera is used to ensure flight heritage and reliability, including the exercise of legacy RS422 interface. Two industrial-grade Prosilica Gigabit Ethernet (GigE), progressive scan CCD color cameras are also used to test and validate fast interfaces to the SpaceCube avionics.

SMART SpaceCube v1.5 avionics application to small rocket systems will benefit from on-board acceleration data. Given volume and power constraints, an IC MEMS accelerometer was chosen. The MEMS IC chip was integrated into the avionics processor board, and provides two axes inertial acceleration data, along the board's plane.

The pressure sensor is used to estimate altitude during ascent and descent, and may be used as an event trigger in later flights. Although board IC sensors are available that would satisfy the current needs of SMART, their use is rather specialized. For this reason and to provide greater flexibility in its location, the use of a discrete, rugged pressure transducer was favored over an IC-type sensor.

Position measurements are essential in establishing not only launch vehicle performance, but also for normal operations once on-orbit. A commercial GPS receiver board was integrated into the SpaceCube v1.5 avionics chassis, and interfaces through one of SpaceCube's RS422 I/O lines. Inertial attitude, acceleration, and magnetic field measurements are provided though an integrated IMU unit. The proper operation of AFSS software will require an addition of a redundant GPS board, and a faster rate IMU than the one flown in SMART. Nonetheless the existing configuration exercises the interfaces and basic architecture, and serves as hardware validation.

Given the Research and Development (R&D) nature of SMART, COTS components were used extensively. Nonetheless, whether cameras or GPS board, all COTS parts were examined carefully, ruggedized, and extensively tested to reasonably assure mission success.

PATH AHEAD – SMART FREE-FLYER

As mentioned, even as SMART's maiden flight is on-board a sounding rocket, its design is that of a free-flyer. To achieve this, the vehicle is capable of operating independently of launch vehicle systems, with its own power and telemetry system. In addition, the vehicle interfaces mechanically to the sounding rocket skin solely through its PAF. Figure 8 shows SMART during skin integration. Note one of the three windows used by the imaging cameras. Figure 9 shows the complete sounding rocket payload during its operational spin test. Aerodynamic window "scuppers" are used to provide "downward" views for GigE Cameras #1 and #2. A "horizon" viewing window is used for the Rocketcam™.

There are few additions required to upgrade SMART to an orbiting micro-satellite. Attitude Control System (ACS) actuators is one, and photovoltaic cells is another. An assessment of capability for future orbital missions constrained the available services to those shown in Figure 10. The payload envelope is variable, and would be mechanically interfaced in the same manner the PAF is interfaced on the opposite end of the vehicle. Available instrument power would range between 12W to 32W, depending on the array option. As the bus itself is fairly robust mechanically, the payload mass may be as high as the bus mass itself, or about 35 kg. The limiting payload factor for this class-vehicle would not be necessarily the mass, but rather the available power.

Figure 8: SMART during skin integration

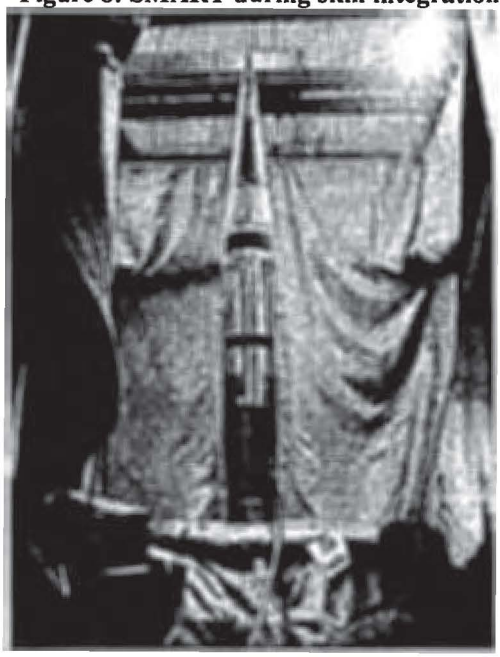


Figure 9: Operational Spin Test

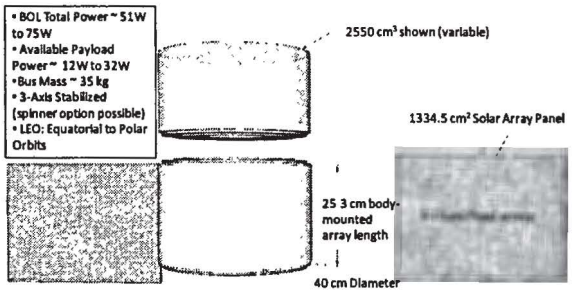


Figure 10: Preliminary Orbital SMART Capabilities

Possible mission configurations include space weather, optical, or radio-frequency payloads, either individually or in some combination. Alternative, technology validation is also an ideal application of SMART. Possible payload configurations are shown in Figure 11.

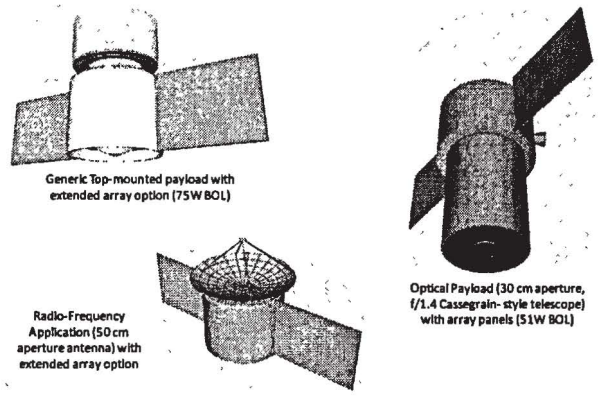


Figure 11: Possible SMART Configurations and Payloads

PATH AHEAD – ORS ENABLERS

From a NASA perspective, SMART provides a step forward in affordable micro-satellites, yielding flexible capability without compromised performance. For ORS, SMART also represents hardware validation of critical enabling technologies, not only for hosting AFSS, but also as a validation tool for Modular, Reconfigurable, and Rapid architectural concepts. As such, ORS would benefit from a system-level exercise from concept call-up to flight, where SMART may be in the midst as a space vehicle demonstration system. This risk-reduction exercise would go a long way in ensuring a successful operational run when rapid-development ORS vehicles come on-line.

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