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ABSTRACT

Under sponsorship by the Operationally Responsive Space (ORS) office, the Air Force Research Laboratory's Space Vehicle Directorate (AFRL/RV) developed a modular nanosatellite approach where hardware and software "black-box" elements can be combined very quickly (possibly less than an hour) to form simple, but functional spacecraft. They are fully compliant with the Stanford/CalPoly CubeSat and Poly-Picosatellite Orbital Dispenser (PPOD) standards, but extend these standards by permitting interchangeability of components. As such, distributed groups can create individual component parts that can be brought together and quickly assembled using plug-and-play (PnP) mechanisms, similar to those in personal computers. The basis of the electrical and software infrastructure is the AFRL Space PnP Avionics (SPA) technology, scaled for nanosatellite purposes (the adaptation is termed "nanoSPA"). Reuse and competitive implementations are promoted, making it possible to choose the best components from many prospective providers. It is envisioned that a secure web-based design system will provide an effective medium for developing design configurations and coordinating the offerings of a community of component developers. Three concept hardware prototypes (one 1U and two 2U CubeSat form factors) were demonstrated, each having fully functional nanoSPA plug-and-play networks and interchangeable components. While some technical challenges remain in fully maturing the concept (such as miniaturization of the plug-and-play interfaces), it is expected that most elements of a nanoSPA system can be available for general use within two years. Before that, AFRL will provide training kits containing the essential elements to permit interested participants early opportunities for developing nanoSPA compatible bus and payload elements.

KEYWORDS: Plug-and-play, SPA, cubesat, nanosatellite

INTRODUCTION

The Air Force Research Laboratory's Space Vehicle Directorate (AFRL/RV) has developed a an approach for rapid creation of satellites. This approach, referred to as space plug-and-play avionics (SPA), combines modularity, standardization, and intelligent interfaces. Systems are arrangements of SPA devices, each designed to look like a "black box" with a common interface. Such standards have been previously attempted. What distinguishes SPA is that each black box is self-describing (through an embedded electronic datasheet), and a network of these devices self-organize to form a system. As such, a number of "black box" SPA devices can be drawn from inventory, rapidly assembled, integrated, and tested by aggregating components, configuring them, and exercising them through a virtual test approach referred to as "test bypass". This SPA capability has been demonstrated through the development of a Plug and Play Satellite (PnPSat) [1].

PnPSat is the first attempt to create an entire aerospace system from plug-and-play (SPA) components. It is a small satellite (~180 kg) designed, developed, and evaluated as a prospective tactical satellite architecture for use in tactical support missions. PnPSat employs a number of novel features, including pre-built panels with a 5 cm *x-y* "pegboard" grid for mounting components. Each panel contains an encapsulated routing system (for data, power, synchronization, and test) invisibly recessed *inside* the panel. Two electrical interface standards have been developed for SPA. The first, SPA-U, is based on the USB 1.1 standard used in personal computers (PCs) [2]. The second, SPA-S, is based on spacewire with plug-and-play protocol extensions [3]. Assembly trials of the PnPSat from bare components to a completed system were demonstrated in timespans of less than four hours.

While the SPA approach to plug-and-play is promising, the concept will remain little more than a technological curio without more direct exposure to prospective developers and users. Just as an operating system requires applications to be useful, SPA requires the existence of SPA components to create SPA systems (aka satellites). Initiating many satellite projects on the scale of PnPSat, however, would be an expensive proposition. While AFRL is considering procurements that involve SPA [4], these efforts are necessarily limited in scope to focus resources on only a few providers. To promote affordable outreach and to germinate the creation of plug-and-play components, AFRL has explored the integration of SPA with CubeSats, since these lower-priced platforms are more accessible to a wide variety of users.

CubeSats, defined as extremely small ($10 \times 10 \times 10n$ cm volume and 1-3kg mass, where n is between 1 and 3) spacecraft [5] have received a tremendous amount of recent attention (our informal assessments have revealed over 150 groups have some research project, recent or ongoing). We feel much of the recent interest stems from the development of a simple but effective dispenser, known as the "Poly-Picosatellite Orbital Dispenser" (PPOD). The PPOD, by fully encapsulating several smaller Cubesats, allows entire satellites to be treated as black boxes, simplifying their integration with launch vehicles. Adhering to the Cubesat envelope specification guarantees compliance with the PPOD. The PPOD separates (to first order) the need for Cubesat developers to concern themselves with the intricacies of launch integration and, conversely, limits the need for launch providers to think very much about the satellites that might be in PPODs.

While Cubesats are among the simplest class of space vehicles, most of them, like their larger counterparts (i.e., traditional spacecraft) are constructed painstakingly, like "Swiss watches". Despite dozens of independent development efforts, the individual components of particular Cubesats, for the most part, have not been interchangeable. The idea of extending SPA-like plug-and-play into Cubesats seems an attractive proposition, since the interchangeability of components between disparate Cubesat developments would likely result in significant economies in effort and reductions in the time necessary to create Cubesats. However, the implementation of SPA had not been previously optimized for compatibility the CubeSat standard. Merging SPA and CubeSats provided an interesting challenge, which became the focus of a recent study, the results of which are described in this paper.

The remainder of this paper is organized as follows. In the next section, we discuss the nanomodular format, the particular way in which we introduce modularity into the CubeSat, permitting their efficient composition from individual components. We then discuss the integration of the plug-and-play (SPA) infrastructure into the CubeSat form, resulting in the "nanoSPA" approach (which retains compatibility with the previously-developed SPA technologies). We then discuss the experimental work, resulting in the demonstration of three ground test Cubesats that fully embody the modular Cubesat and SPA approaches. Finally, we discuss current project status.

THE NANO-MODULAR FORMAT

The Cubesat standard, being primarily an envelope specification, admits many creative implementation possibilities. Some implementers fashion their own chassis structures from raw materials. At least one Cubesat kit has been made commercially available,[1] and a number of groups have studied the PC104 form factor and bus as a possible common backplane, with a few vendors offering modules compatible with each other. Even these options, while reducing the overall effort needed to create a Cubesat "from scratch", require intensive customization, and the integration of software, electrical, and mechanical elements even with these components can be involved. As such, we felt that development of a "take-apart" Cubesat structural concept would simplify development and promote component interchangeability and reuse. We explored a number of design concepts, emphasizing as criteria modularity, maximizing usable interior volume, and ease of assembly and integration.

An initial concept for the structure is shown in Figure 1 (top panel) and Figure 2 (side panel). Eventually, this concept evolved to the symmetric arrangement of hinged panels or *facets* shown in Figure 3. The facets were designed to accommodate very small plug-and-play components, each facet having a target volume of 70mm×70mm×12.5mm (in the case of a "1U" CubeSat). We call the facets of this approach "the *nano-modular format*" (NMF) and have adopted nomenclature similar to that used to express sizes in CubeSats (e.g., 1U, 2U, 3U). For example, the 1U Cubesat in Figure 5 is comprised of six, 1×1 NMF facets. A generic component built into a 1×1 NMF facet is shown in Figure 4.

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[1] Pumpkin, Inc., San Francisco (http://cubesatkit.com)

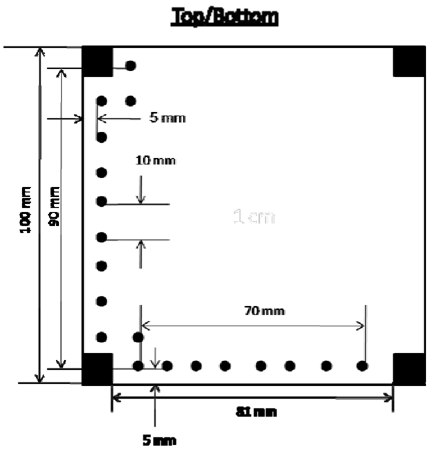

Figure 1. An initial concept design of a top structural panel. The proposed form factor was 70 mm × 90 mm × h mm.

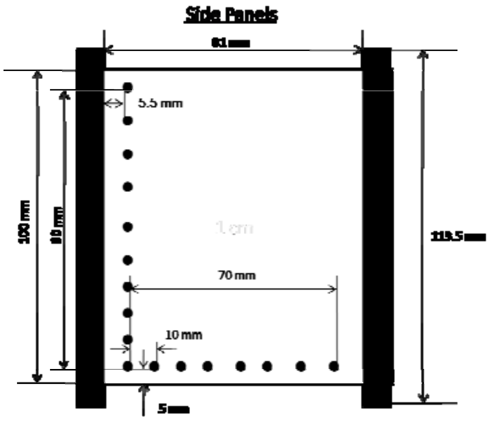

Figure 2. An initial concept design of a side panel.

As previously stated, the target interior dimensions of a 1×1 NMF facet is 70mm×70mm×12.5mm. It was originally envisioned that a set of six modules of this dimension would form a closable, hinged assembly (a completed 1U CubeSat *sans* rails, which are attached in final assembly before insertion into a launch dispenser) as shown in Figure 5. In fact, based on this facet size, the arrangement of six facets forms a hollow shell, having a space capable of accommodating a 5cm cube in the center as a "reserve volume", along with a sort of "raceway" between this inner and outer shell to accommodate cabling. This arrangement is depicted in Figure 6. In this figure, the interior reserve volume has been "claimed" by one of the nanomodules, which could for example correspond to the case of a tiny control moment gyroscope module that might require the placement of torquing motor actuators near the mass centroid of the CubeSat.

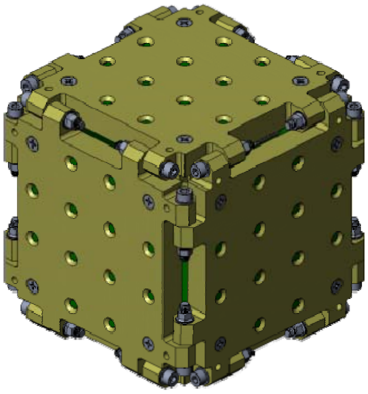

Figure 3. The final design for a 1U cubesat using the NMF and standard mechanical interfaces .

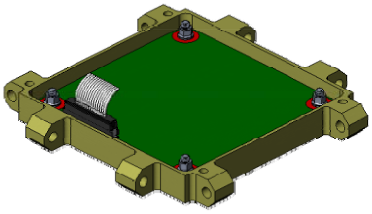

Figure 4. A nanomodule (Cubesat component), based on the 1×1 nanomodular format (NMF), which doubles as a panel for the Cubesat.

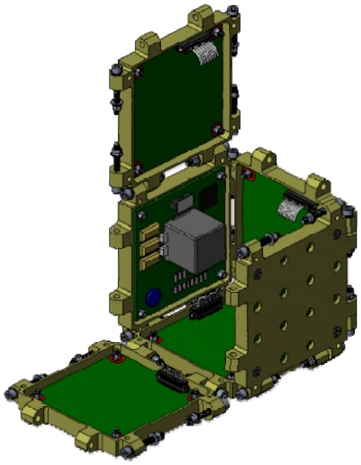

Figure 5. View of CubeSat base on arrangement of six 1×1 nanomodular format (NMF) nanomodules, in opened view. Nanomodules are mounted within the panels and the structure is folded up into a cube.

More generally, however, it is possible to define a *maximal symmetric envelope* (MSE), as shown in Fig Figure 7. "MSE" in this case is simply defined as the envelope of the largest shape that can be used for any nanomodule such that no interference occurs when six identical modules are folded together to form the structure shown in Figure 3.

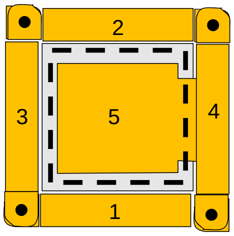

Figure 6. Volume utilization concept. Nanomodules 1-4 form side panel. Nanomodule 5 reserve volume is "claimed" by module 4. Dashed line represents raceway for cabling.

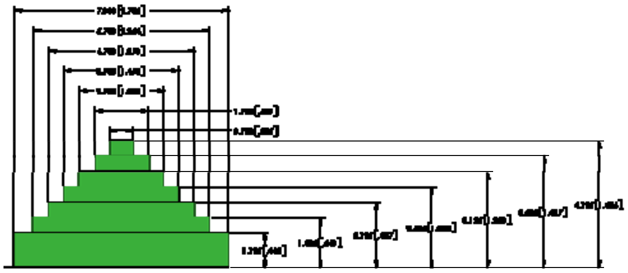

Figure 7. Maximal symmetric envelope (MSE) for nanomodules. (Dimensions are notional).

The modularization approach established by NMF has two main advantages. The panels have been designed so that each one can be developed as a separate nanomodule (integrated and assembled individually), then brought together and integrated to form spacecraft, analogous to the way mice, keyboards and USB components are brought together to form a personal computer. Additionally, the modular structures give the ability to build larger satellite structures out of smaller panels.

Just as it is possible to define other Cubesat sizes (e.g., 2U, 3U), it is also straightforward to define other NMF facet sizes. The outlines for a number of different NMF configurations are shown in Figure 8. Included for comparison (Figure 8a) is the 1×1 NMF already described. The next larger facet is the 1×2 NMF (Figure 8B), which becomes the elongated side panel of a 2U CubeSat. Similarly, the 1×3 NMF (Figure 8c) becomes the side panel of a 3U CubeSat.

While the focus of this paper (and much of our present interest) is centered on the CubeSat platforms, the NMF scheme admits the flexibility to support special extended formats. For example, the 2×2 NMF shown in Figure 8d does not correspond to a traditional CubeSat form factor. Obviously, the NMF scheme can be extended to a wider variety of *n*×*m* NMF configurations.

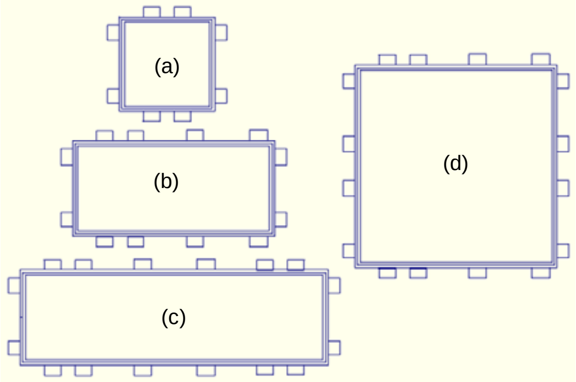

Figure 8. Outlines of nanomodular format (NMF) facets. (a) 1×1 NMF. (b) 1×2 NMF. (c) 1×3 NMF. (d) 2×2 NMF.

The NMF facets can be arranged ("mix and match") in heterogeneous compositions to form CubeSats. This capability can be seen in Figure 9. Additionally, shown in Figure 9, is a 2.0cm×2.0cm mounting pattern. This enables (say) the 70mm×70mm surface of a 1×1 NMF to be subtended so that smaller modules or components can be mounted within the volume of a single facet using the same mounting pattern.

Figure 9. An example of a 2U cubesat (20 cm x 10 cm x 10 cm) based on a combination of 1×1 and 1×2 NMF facets.

Other points regarding the NMF approach are worth noting. First, the use of hinged structures dramatically simplifies the "serviceability" as well as assembly of Cubesats. Opening the structure to expose interior elements is a straightforward operation. In many cases, the CubeSats based on NMF facets can be operated *while* opened. We believe the 1×1 NMF size in particular is convenient for implementing encapsulated circuitry, as these facet dimensions are comparable to those of complex hermetic hybrid (multichip module) assemblies found in larger, traditional aerosapce systems. As such, 1×1 NMF facets might be useful in more complex assemblies in other (non-CubeSat) systems. This improves the idea of reuse. For example, a dense storage module for CubeSats might also be a dense storage module for a 1000 kg satellite. This interchangeability is aided when both small and large systems are "SPA-ready". The integration of SPA in NMF, which enables small modules to "plug-and-play" into larger systems, is described in the next section

INTEGRATION OF SPACE PLUG-AND-PLAY AVIONICS INTO CUBESATS – "NANO-SPA"

In order to understand the challenges in mapping SPA to CubeSats, it is useful to review basic SPA concepts ("SPA 101"), then review how the migration to CubSats has been implemented.

"SPA-101"

SPA is actually a suite of technologies, including interfaces, networks, hardware, software, ontological, and test concepts, which are briefly reviewed here. The concepts are described in the context of SPA-U (USB-based SPA), followed by a brief discussion of extensions to the SPA-S (Spacewire-based SPA). The implementation of SPA is defined in a series of standards maintained by AFRL with the assistance of the AIAA.

Interfaces. In the nomenclature of SPA, a SPA-*x* network is based on the extension of some base interface technology (*x*) to accommodate the services of comand, data transport, power, and synchronization. The first SPA networks was based on the USB standard. The SPA team chose USB 1.1 (limited to 12 Mbps), since the associated components were considered easier to migrate to radiation-hardened form than would be the higher-performance USB 2.0 standard. Even as an aggregate rate (since USB is time-shared, the 12 Mbps is a constraint on the entire network), USB 1.1 was deemed to have sufficient bandwidth for > 80% of the components of typical spacecraft. We expected high-performance components to be handled with the higher performance tnetworks that were eventually developed (e.g., SPA-S) and continue to be explored (e.g., SPA-10). While the SPA development team went to great lengths to maintain the integrity of the USB 1.1 standard (this is important, since unmodified intellectual property cores can be used directly), SPA-U **is not** USB 1.1. In order to drive the higher power components of spacecraft, it was necessary to supplement USB with additional power delivery, in the form of two additional conductor pins at 28 VDC (the most prevalent voltage used in contemporary spacecraft). To provide a synchronization mechanism, two additional pins were included in the interface definition of SPA, namely being a one pulse/second (1PPS) RS-422 pseudo-differential signal pair. The 1PPS signal on a SPA device is normally a receiver (which may be ignored if a device does not need to be synchronized), except when a SPA device is actually a source of synchronization signals, in which case the device *drives* the 1PPS signal.

Networks. SPA-U networks are defeined as networks containing two or more SPA devices. At least one device must serve as a host, following the convention of typical USB networks (in which a computer is usually a host). Consistent with our normal experience as PC users, in order to exapnd a USB network, we must add a hub to expand the ports available to connect other USB devices, which are either endpoints (examples include keyboard, mice, "thumb drives") or other hubs. This same conceptual model applies in SPA-U. The most obvious difficulty is that in the SPA-U hubs, in addition to routing the USB data/command signals, it is necessary to broker 28V power and 1PPS signals. SPA-U hubs are even a bit more sophisticated than this (they can, for example, dynamically reorient port configurations to accommodate multiple hosts and deal with host failures), but we shall be belabor these details further here. A typical generic SPA-U network for a spacecraft is shown in Figure 10. The command and data handling (C&DH) processor, typically the central computer of a spacecraft, serves logically as the SPA-U network host.

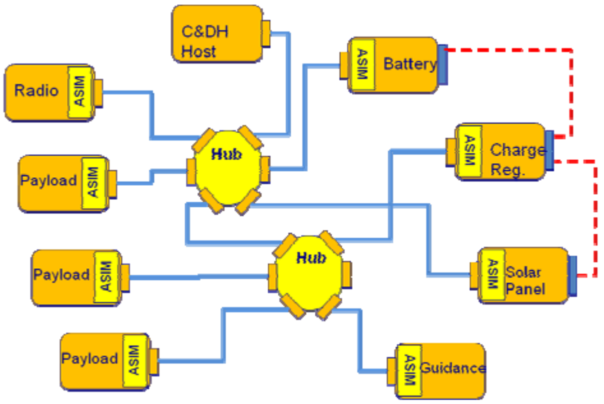

Figure 10. SPA-U network (solid interfaces are SPA-U connections; dashed interfaces are specialty power generation bus connections).

The canonical components and subsystem of the spacecraft become SPA devices, connected to the C&DH through single-point SPA-U interface connections, expanded through the introduction of SPA-U hubs. The single-point connection philosophy simplifies the concept of quickly building a SPA system, especially since the network is "topology agnostic", meaning that the order and specific position of components within a SPA nework are unimportant. SPA-U components, therefore, can be plugged into a SPA-U network in varying quantities and positions as needed to implement a specific design without altering system hardware and software. Power subsystem devices (such as batteries and solar panels) deviate from this concept, since while these components are also SPA devices (with a SPA-U interface), they require special interconnections between each other to establish the power grid (that is, the batteries and solar panels form the 28V bus using a battery charge regulator).

SPA Hardware. SPA devices are defined as any component supporting a SPA interface. For SPA-U, devices can either be SPA-U endpoints, SPA-U hubs, or SPA-U hosts. Since most pre-existing "legacy" components do not natively support SPA-U, modules referred to as applique sensor interface modules (ASIMs) have been developed as a sort of sophisticated "adapter". ASIMs are special-purpose hardware modules designed to manage SPA devices, built in radiation-tolerant form (when used in flight system development). ASIMs include microcontrollers that are programmed to generate the native command structures of their *client* devices, and encapsulate the electronic datasheets that describe the devices. They play a role analogous to USB interface chips (Figure 11), which launder the USB interface to a generic breakout interface suitable for integration with many typical peripheral components. Similarly, ASIMs provide a SPA interface that complies with a SPA standard (such as SPA-U) as well as a generic breakout interface, suitable for integrating with the raw interfaces and circuitry of new and legacy components.

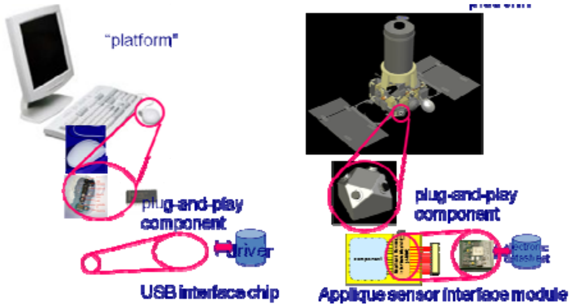

Figure 11. Comparison of plug-and-play in personal computer to SPA.

In practice, ASIMs are expected to be embedded in these components (as shown in Figure 10), such that the component plus its ASIM would be treated as an integral "black box" SPA device. ASIMs are not mandated as a standard themselves, but are used to greatly simplify the burden of converting devices into a form that can plug-and-play with other SPA components.

SPA Software. One of the most important elements of SPA is the system of software that supports the unified mechanisms for discovering SPA devices, SPA applications, and dynamically organizing them automatically to form an entire system. The software system for this is called the *satellite data model* (SDM). SDM is not formally a service-oriented architecture (SOA), but operates in an analogous way. It is depicted notionally in Figure 12 as a vertically-layered model. The SDM is characterized by a number of lightweight modules that are given names ending in "manager", such as the *data manager*, which performs the central role of registering SPA devices when they are found in the system. Registration basically amounts to exposing the services of all devices and managing subscriptions to these services (from other devices). SDM enforces a discipline of software reuse in the same way, as it expects user applications to also contain electronic datasheets. The services defined in the datasheets of software and hardware are at one level indistinguishable to subscribers for these services, providing an unusual abstraction that at one level blurs the distinction between software and hardware. SDM has been ported to Linux (with VxWorks ports in development as of this writing) and is maintained presently as open-source software available through AFRL.

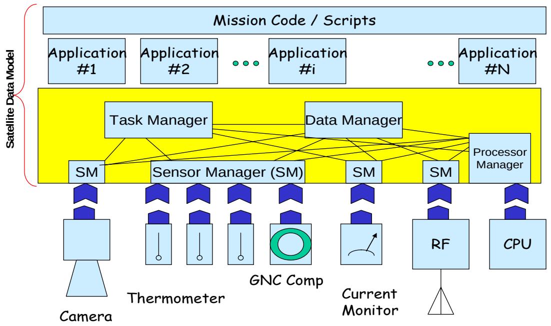

Figure 12. The satellite data model (SDM).

SPA Ontology Concepts. SPA is fundamentally a data-driven architecture. This notion is strongly enforced through the electronic datasheets embedded in every SPA device and SPA software application. Formally, the electronic datasheets are XML-based and called eXtended Transducer Electronic Datasheets (XTEDS). They are an important part of the black box abstraction central to SPA, since at one level they contain a description of the "knobs" that may be turned (i.e., commands), the measurements that can be extracted, and device characteristics and properties useful to other applications within a SPA system. A simplified hierarchical diagram of the organization of an XTEDS document is presented in Figure 13. The foundation of XTEDS are "atoms" of data drawn from a common data dictionary (CDD), composed into variables, one or more of which comprise messages, one or more of which comprise interfaces, etc. We say that XTEDS enforces data centricity in the SPA concept because (practically speaking) functions not described in an XTEDS do not exist in the "SPA universe", meaning that there is no standard approach to access services not described in the XTEDS.

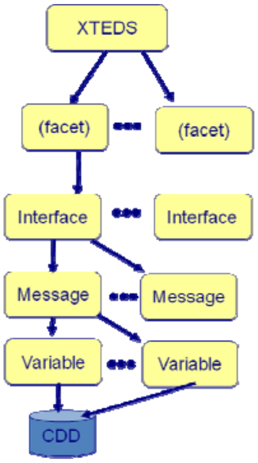

Figure 13. Conceptual organization of eXtended Electronic Transducer Datasheet (XTEDS).

XTEDS support hierarchy informally through the implied chain of SPA device/application interdependency. A high-level SPA application can, for example, subscribe to the services of several other SPA devices and applications, which in turn may subscribe to others. A SPA power system may seem to be an integral component, but in fact may be an ensemble of SPA elemental devices (i.e., a SPA battery, a SPA solar panel, a SPA battery charge regulator) that can treated itself as an overall (if not dispersed) black box. Ultimately, we would regard an entire system, such as a spacecraft, as having a platform-level XTEDS. In some cases, the idea of interfaces, as shown in Figure 13, are useful for enforcing a number of compartmentalized roles for systems (or components). As an example, if a spacecraft can be thought of as having an overall XTEDS, then as a (really complex) "black box", the spacecraft will have one role as an object in a launch system (a launch "interface"), a different role to a satellite operator (an operator's console "interface"), another to a satellite service user (a user "interface"), and still (possibly) other roles for peer satellites in an ad hoc network.

Test Bypass. The hardware (ASIM) and ontology concepts of SPA make it straightforward to pervasively embed testability through "hooks" that exploit the universal intelligent SPA interfaces and the definition of functionality inherent in the XTEDS description. The linkage for exploited these hooks is referred to as "test bypass". Currently, the test bypass port (TBP) is an optional secondary connection in ASIMs, consisting of a simple, two-pair RS-422 interface (i.e., one pair directed in, the other out from the SPA device). The pins for the TBP can be collocated with the primary single point SPA connection (as done in PnPSat), or relegated to a secondary connector (as done in early SPA-U configurations). The network consisting of all TBPs on all SPA devices forms a secondary network that can be manipulated independently and non-intrusively to the primary satellite electrical network. This test bypass network is commanded externally (very analogously to a JTAG [6] network) during assembly, test, and integration. In test bypass, specific services within devices can be over-ridden with artificial ones produced in simulation. The actual temperature of a SPA thermometer, for example, can be replaced with a synthetic value. This ability to drill down and manipulate raw data variables provides a sophisticated debug infrastructure, analogous to that available to software developers in commercial integrated development environments (IDEs).

Extensions of SPA -- other SPA-x Standards. While the present discussion of SPA has focused on SPA-U, the concepts largely apply to other forms of SPA, including SPA-S (spacewire-based SPA, used in PnPSat) and SPA-10 (a 10 gbps optical interface, presently in development). The most significant differences in SPA-S relate to its bandwidth (theoretically up to 625 Mbps) and its nature as an egalitarian network (i.e., no central host, as in the case of USB), which required modified ASIMs (to support spacewire physical layer and routing tables), alternate SPA routers (as opposed to hubs in the SPA-U case), definition of a SPA messaging protocol, the use of the network manager in SDM. Spacewire, not intrinsically a plug-and-play technology, required extensions to support SPA-S in the form compatible protocols that support automatic network organization. In SPA-U, the SDM's sensor manager directly manages the root(s) of USB networks, obviating the need for the features. While in fact most platforms to date have been developed as either SPA-U or SPA-S systems, it is possible to bridge SPA-U components into SPA-S systems through an adapter which launders a USB network into a SPA-S endpoint.

Hosting SPA onto CubeSats

We will refer to the SPA embodiment for CubeSats as "nanoSPA". We chose SPA-U as the base protocol for nanoSPA, due to its relative simplicity and the ubiquity of USB (i.e., part of every modern personal computer). There were several barriers to hosting SPA-U in the dimensional constraints of CubeSats, as well as their limited electrical power budgets. In fact, besides miniaturization and power reduction, the only critical constraint in migration SPA-U to CubeSat form was the choice of the electrical voltage standard. Whereas 28V is a convenient standard for most spacecraft, this constraint was debilitating for CubeSats since their simpler electrical power systems do not typically generate this level of voltage. As a compromise, we defined the PnP CubeSat standard to be 5V for operation in CubeSats, with the ability for most nanoSPA devices to tolerate 28V. We say “most”, as it is conceivable that a number of nanoSPA devices could be attractive for reuse in larger satellites, such as mass storage devices, space weather instruments, and attitude sensing devices. However, it is also likely that a number of nanoSPA devices are not useful for larger satellites, such as tiny reaction wheels and most of the CubeSat power system elements.

EXPERIMENTAL WORK

In this section, we describe the work leading to the creation of three ground demonstration PnP CubeSats. We briefly describe some of the canonical spacecraft subsystems and how we undertook their mapping into SPA devices.

This work was completed Summer 2008 at AFRL through an AFRL-led student team, working closely with a small group of industry and academic partners, supported through supplemental funding provided by the Office of Operationally Responsive Space (ORS) at Kirtland AFB, NM. To provide a mission context, our team focussed on space weather / space environment monitoring as a source of mission concepts, though the interchangeability inherent in SPA allows the resulting toolbox of components and technologies to be exploited by a much greater variety of mission concepts.

Electrical Power System (EPS)

The EPS is central in supporting the activities of operational CubeSats, including communications, attitude control maneuvers (if applicable), computation, and payload operations. Every other subsystem of the PnP Cubesat must be designed around the parameters provided by the structure and the EPS that can be housed within. CubeSats, suffer sharply from limited power generation facilities, due to limited surface area for mounting solar panels. For example, a solar panel working at 29.9% efficiency can produce 4.0 W under ideal conditions over an area of 100 cm^2. Conditions are never ideal, and the area covered is not exactly 100 cm^2. In reality, the typical power available to a 1 unit cubesat is 2 W or 2.5 W of continuous power in sunlight. Deploying solar panels (to increase the ability to gather power) is an attractive concept, but adds additional requirements a for a deployment subsystem and a guidance subsystem (to maintain sun tracking).

Classically, the EPS must be able to supplement the energy harvested from solar panels with batteries during high power activities (which may reqire much higher peaks than the average power output of the solar panels can supply)and to maintain satellite functions through eclipse. The canonical EPS for a simple system can be viewed as having three components: solar panels, batteries, and battery charge regulators.

We next describe idealized embodiments for a SPA-based EPS, and what we actually implemented for the experimental configuration. A summary of these embodiments is shown in Figure 14.

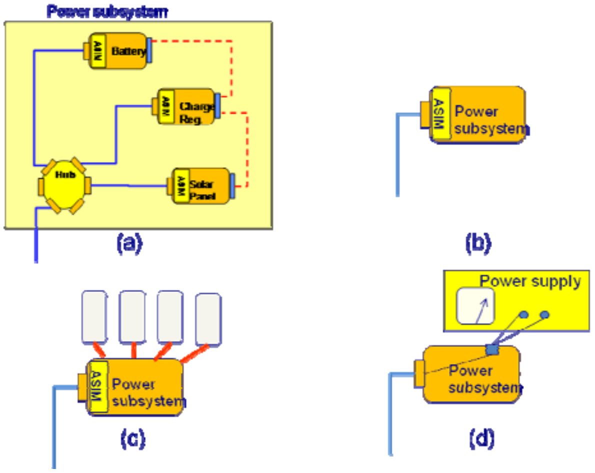

Figure 14. SPA-based EPS embodiments for a very simple satellite. (a) Discrete SPA modules. (b) Tightly-coupled SPA module. (c) Tightly-coupled SPA module with accessory panel connections. (d) “Ground” configuration used.

In principle, it is straightforward to assemble a power subsystem from constituent elements. This approach was depicted in Figure 10, and the relevant sub-network is shown in Figure 14a. In this case, the power subsystem is fractionated into individual SPA components for the canonical system, networked using a SPA hub. The ensemble, as previously discussed, can be thought of as a single composite SPA device, using either the battery charge regulator ASIM as the dominant XTEDS (or even by defining a separate XTEDS within a “helper” shell SDM application that could accompany the power components). An .alternative embodiment, referred to as “tightly-coupled” achieves the same result using a single SPA device (Figure 14b). In this case, one could simply create effectively an OEM-like approach in which a satellite user need only consider the power module, which we envision could conveniently be integrated with a 1×1NMF or 1×2NMF structure having a single nanoSPA-U connector. This SPA-U module would be a full power solution for a CubeSat, having a body mounted solar panel on its exterior and the battery, BCR, and ASIM within the NMF facet. Realistically, in this case it would make sense to provide accessory connections (as shown in Figure 14c) to allow a few other body mounted panels to be opportunistically placed on other NMF facets making up the CubeSat.

In our brief development program, unfortunately, we chose a very “low tech” expedient for the power subsystem, shown in Figure 14d. This inelegant (but effective) work-around employed an empty 1×2 NMF facet having inside a nanoSPA-U connector, which passed two wires to an external 5V power source. As an additional expedient, we did not prepare an ASIM or even a shell XTEDS (as we probably should have), given the relative simplicity of the 5V power “problem” in a lab environment where power is still ubiquitously available.

Guidance, Navigation and Control (GNC)

We believe that there are some mission domains in which GNC may not be necessary, though omitting one sharply limits the ability to generate power, complicates communications, and constrains the types of payloads that can be employed (some space environment monitoring missions, for example, may only require exposure to the environment, and do not “care” about attitude). Data collection for free-flying CubeSats without GNC may prove to be difficult because the positioning information for a given recording from an instrument could be dependent on a spacecraft position and time.

Determination. Spatial determination and control of the satellite is a difficult GNC task. Many Cubesats are not capable, through the satellite itself or the associated ground station, of providing positioning information about the satellite. These processes are computationally intensive, requiring high amounts of power and/or are technically difficult, such as ranging through the communications subsystem. Most projects use two line element sets provided by NORAD for their spacecraft ephemeris.

Control. In addition to the lack of positioning information, the ability of Cubesats to control their position does not currently exist, primarily because the requirement for a propulsive capability does not exist. However, the orbital lifetime of the spacecraft is exponentially proportional to the altitude of the spacecraft. This is very prohibitive to the number of possible mision sets in which nano and picosatellites can preform.

GNC Implementation Concepts. Implementation of the GNC subsystem is constrained by the physical properties of the Cubesat (center of mass, mass moments of inertia), rather than the state of electronics technologies (size, power, radiation tolerance). The reduced size of the satellite is actually advantageous for the GNC system, but it may difficult to develop all of the hardware required to perform GNC solutions within NMF facets (we discussed for example, the prospects of engineering a miniature CMG to fit the reserve volume in Figure 6). The GNC subsystem is further complicated by strong mission dependencies. The creative challenge then is to devise a modular concept, compatible with nanoSPA and NMF faceting, while providing flexibility with a bounded number of component types.

Fortunately, it is not necessary to completely start from scratch. GNC solutions have been developed for various CubeSat projects, such as AAU CubeSat[7], AAUSAT II[8], and ION[9]. These employed three-axis magnetic sensing and magneto-torquers to control the attitude of the spacecraft. The concept is applicable for multiple attitude control manuvers such as de-tumbling, spin stabilization, and coarse 3-axis stabilization of the spacecraft. The use of magneto-torquers is a fairly robust and simple mechanism for LEO cubesat missions, which easily fits within a Cubesat.

Currently, much of the work on the GNC for the PnP Cubesat has been the cataloging of existing COTS parts and technologies which would fulfill the requirements of multiple GNC solutions and fit within a cubesat form factor. Small individual components, such as miniature reaction wheels, seen in Figure 15, or complete attitude determination and control (ADC) solutions, such as the Intellitech IMI-100[10] currently exist. A small catalog of components which include various optical navigation sensors (sun sensors and star trackers), magnetometers, torque rods, reaction wheels, deployable mechanisms, has been compiled in the goal of being able to create multiple COTS ADC solutions.

GPS data can provide accurate position and velocity knowledge of the spacecraft, which can be used for the spacecraft ephemeris and can be used to better know the location of the spacecraft when data is recorded. As such, GPS receivers capable of working in the spacecraft environment (altitude, velicoty, radiation) are attractive prospects for nanoSPA GNC modules. Terrestrial receivers already exist small enough to fit within a NMF facet and requiring very little electrical power.

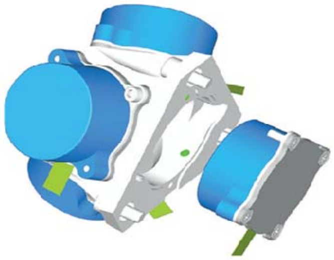

Figure 15. Miniature reaction wheels designed specifically for nano and picosatellites.

De-orbiting Considerations. De-orbiting Cubesats will become an increasing concern as quantities increase. A space weather mission, for example, may play multiple cubesats into MEO or HEO orbits to map the radiation background in those orbits. However, a Cubesat in a MEO orbit will never come out of orbit, and this can also be true for a Cubesat in a HEO orbit, depending on its specific orbital parameters. In order to be able to preform these mission sets, the development of a propulsion system which is capable of lowering the satellite's perigee so that it de-orbits within the required lifetime will be necessary. We believe it will be possible to develop a nanoSPA de-orbit module to meet some of these challenges. Requirements for such modules include the ability to interface with the structure and the ability to provide adequate "delta-V" to de-orbit a cubesat from a high altitude orbit.

Communications

The ubiquity of communications is such that it is hard to imagine conducting even simple missions with it. The traditional modalities of communications include: timing, tracking, telemetry and control (TT&C); payload (user) communications; and (more rarely) inter-satellite communications. We next describe a few prospective SPA embodiments, and the approach used in our demonstration configurations.

It is conceivable that for extremely simple missions, these modalities could be compressed into a single transmit-only transponder, which conveys limited quantities of mission and telemetry data. AFRL previously studied the possibility of embedding emergency beacons in spacecraft, exploiting the multiple access mode of the tracking and data relay satellite system (TDRSS) [11]. This architecture is attractive as it permits satellites to be placed in practically any orbit (i.e., within 20,000km) of the nearest TDRS and requires reasonably modest (possibly software only) accommodations in the existing ground architecture to support of large constellation (~500) of CubeSats, each having a 10kbps data rate (10% duty factor). This particular design point corresponds to a 5W effective radiated power, which is manageable for Cubesats when averaged using < 10% duty factor. We believe that it is possible to engineer such a transponder within a 1×1 NMF facet using a surface mount antenna.

Of course, many missions will require two-way communications. Some previous Cubesats have employed a pair of whip antennas, placed 90° from each other for circular polarization [12]. Being omni directional, these whip anteanna are advantageous because there are no pointing constraints. There is also no gain with this antenna, leading to a smaller signal to noise ratio, limiting the amount of data that can be transmitted between the satellite and the ground station for all of the overflights of the ground station. An addition difficulty is the sparsity of allocated radio frequencies for radio transmissions (ground to spacecraft and spacecraft to ground). Cubesats have typically used amateur radio frequencies between 144 to 148 MHz, 420 to 450 MHz, and the 2.4 GHz spectrum, which have contention with amateur operators.

More sophisticated comunications solutions are possible, and some are presently under study at AFRL. One gaping deficiency in any of the communications approaches described is the lack of an effective Type 1 (NSA-certifiable) encryption function. This deficiency may be less problematic for transmit-only systems, which can never by "hijacked" since they cannot receive any commands. We estimate that an effective configuration would need to be smaller than a matchbook, with a mass < 30g, and power consumption < 50mW for data rates ~10 kpbs.

For the experimental demonstration CubeSats, we developed an IEEE 802.11 radio with co-integrated command and data handling processor (discussed next) within a 1×2 NMF facet (though the antenna protruded outside the envelope dictated by the CubeSat standard). The use of 802.11 as a radio architecture would not likely ever be compatible with a true flight application, but for the ground demonstration system provided a realistic "look and feel" which from a SPA perspective woud translate very transparently to actual flight solutions. We argue "transparently" in the way that users can connect "transparently" through browsers to the internet, whether they use wireless, Ethernet, or dial-up connections. In the demonstration system, an ordinary laptop serves in the role of a ground station through use of its wireless (802.11) connection.

Command and Data Handling (C&DH)

The command and data handling (C&DH) subsystem is often thought of as the brains of a spacecraft. It is certainly the core of the nanoSPA concept. This subsystem, which encompasses the avionics, data storage, day to day autonomous operations of the spacecraft and other operational sequences of the spacecraft, has been tailored to provide the highest level of modularity enabling the plug-and-play concept. In the case of SPA-U, the C&DH must support running SDM and hosting the USB part of the SPA-U network. It could alternately generate (if equipped with a time reference) or source the 1PPS network, and expects to receive power through the power pins of its SPA-U port (from the EPS). In order to connect to any other nanoSPA devices, at least one nanoSPA hub is required to extend connectivity. The C&DH must host software in addition to SDM, namely a minimum set of SDM applications necessary to perform required mission operations.

One significant constraint in migrating SPA-U to typical devices capable of fitting into NMF facets is in the physical overhead represented by the ASIMs. For the experimental configurations, ASIMs of the same design used in PnPSat were used, reconfigured to support SPA-U instead of SPA-S. Each ASIM (at 50mm x 50mm), occupied most of the floorplan of a 1×1 NMF facet. At 1-1.5W, the power consumption of a few ASIMs would be prohibitive for a real SPA-U based CubeSat. Nevertheless, we used these ASIMs to support the deomstration configurations. Since the purpose of these demonstrations was mostly to establish the basic feasibility of SPA migration to CubeSat the form factor, and given the fact that lab power was abundant, the oppressive overhead of these old ASIMs was not a primary concern. Interestingly, the ASIMs, though designed for 28V operation, were also operable at the 5V Cubesat bus voltage.

An ordinary USB four-port hub was used as a stand-in for the SPA-U hub, powered when connected to the mock power source. Unlike the more sophisticated SPA-U hubs used in previous work, this hub did not support dynamic rewiring of ports. This hub also did not route 1PPS signalling, essentially deprecating the synchronization within the demonstration systems.

The C&DH module, colocated with the communications subsystem, was housed in a 1×2 NMF facet. The C&DH used was based on an Intel PXA270 (Xscale) processor, supporting a full Linux distribution with SDM running "on top". Unlike the ASIMs, the PXA270 uses very little power (typically < 1W), though the amount of power was somewhat ovserved by the resident 802.11 module.

Payload Provisioning for nanoSPA

Payloads, being the reason satellites exist, demand the most generous provisions of size, weight, and power possible within a given class of spacecraft. The results of a simplified analysis of the possible provisions for payload mass and power for different-sized CubeSats based on nanoSPA is shown in Table 1. This analysis is based on the assumption of a 1×1 NMF CDH, 1×1 NMF radio, and 1×1 NMF EPS with auxiliary cells placed on available panels. We assumed that a GNC subsystem is included, consisting of a single 1×1NMF facet, plus the interior compartment suggested in Figure 6. (Obviously, in mission concepts not requiring GNC support, the resource allocations to payload can be further improved). Power calculations are slightly derated from our prior discussion, and we assume 1.5W, 2.5W, and 4W orbit average power (net) for 1U, 2U, and 3U Cubesats, respectively. The C&DH processor is allocated 0.6W continuous for the 1U case, increasing to 0.8W for the 3U case. The TT&C module is assumed to require an averaged allocation of 0.25W universally. Finally, the GNC power consumption is assumed to require 0.25W (orbit average) for the 1U case, scaling linear in power consumption with system mass.

Table 1. Estimated resource availability (best case) for payloads in nanoSPA-based CubeSats

nanoSPA CubeSat size	Payload Power (total) W	Power Fraction (%)	Payload Mass (total) (kg)	Mass Fraction (%)
1U	0.4 (1.5)	27%	0.25	25%
2U	1.05 (2.5)	42%	0.73	37%
3U	2.2 (4)	55%	1.63	54%

While the allocations of mass and power for payload are minimal in these CubeSats, this analysis demonstrates the incentive to use the largest CubeSat possible to extract more resources for the payload. In other words, the overhead for the bus grows less slowly for larger CubeSats, leaving more resources for payload. We do not believe that these provisions are dramatically out of line with other CubeSat architectures.

Demonstration Configuration

Three "concept satellites" based on the nanoSPA architecture were constructed and demonstrated. We use the term "concept satellite" in mimicry of the notion of the concept cars of Detroit. AFRL, in its responsive space testbed facility (Kirtland AFB, NM) had previously demonstrated a concept satellite for a ~200kg bus, which became the forerunner of the PnPSat. The three concept satellites based on nanoSPA were considerably more modest (< 5kg), but analogously relevant as precursors to future flight-worthly nanoSPA platform implementations.

Two nano-SPA concept satellites were based on the 2U form factor, and one nano-SPA concept satellite was built in the 1U form factor (Figure 16). The 1U concept satellite was never populated (we did not have a 1×1 NMF C&DH during the study), and was a "structure only" prototype (all NMF facets were created by Spaceworks, Scottsdale AZ). The 2U CubeSat, however, was fully functional, consisting of four 1×2 NMF facets and two 1×1 NMF facets. Sometimes, a 1×2 NMF panel was replaced by two, 1×1 NMF facets. The 1×2 NMF C&DH/TT&D combination module (built by Vulcan Wireless, San Diego, CA) included a full SDM system (implemented by Utah State University, Logan, UT) with tightly-coupled software to support the radio system, whch used 802.11 as a placeholder for more suitable communications concepts in the future. The EPS modules were similarly placeholders, as shown in Figure 14d. A locally purchased USB hub was dismantled and transplanted into a NMF facet with connectors.

Figure 16. Concept satellites in the form of assembled nano-SPA based CubeSats. The left CubeSat is a 1U form factor, the right being a 2U form factor. The solar panels on the 2U are "mock", and the protruding 802.11 antenna would not be suitable in an actual flight system.

The "payloads" for the concept nano-SPA CubeSats consisted of "vintage" ASIMs (Data Design Corporation, Gaithersburg, MD), interface to thermometers as the source of "mission data". We demonstrated the ability to add and interchange multiple ASIMs dynamically to each of the 2U CubeSats, dynamically, while operating these spacecraft using the 802.11 links to laptops. Rail brackets, designed for attachment to finished CubeSats were attached and a simple clearance test was performed on a PPOD to verify to first order the mechanical compatibility of the nanoSPA-based CubeSats to this universal dispenser. The ability to open up the CubeSats during integration (Figure 17) was very useful in accessing components and debug / troubleshooting. All key concepts of SPA were demonstrated in this embodiment (except test bypass), and these concept nanosatellites are the smallest ever demonstrating the principles of SPA.

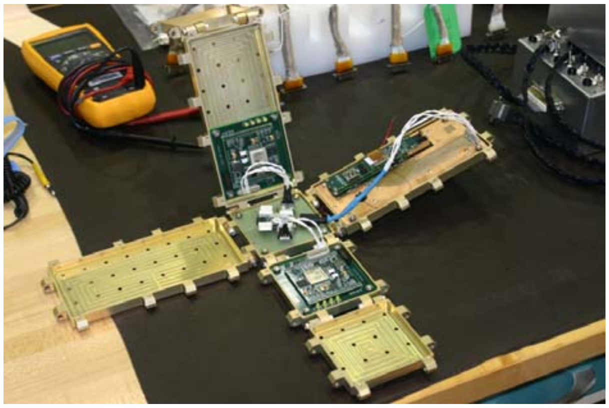

Figure 17. nano-SPA 2U CubeSat operating in "open" configuration. Interiors of several NMF facets, including the C&DH/TT&C module (right), hub (center of folded system), and two ASIMs "payloads" are shown.

CURRENT PROJECT STATUS

The exercise of mapping SPA into the CubeSat form factor has revealed both challenges and opportunities, and these insights have affected the research frontiers of SPA, both for CubeSats as well as larger satellites. We briefly discuss these points in this section.

Some challenges in mapping SPA into CubeSats were understood a priori, such as the need to miniaturize the avionics. To that end, we are investigating aggressive redesigns for the ASIM to reduce size, weight, and power. Ideally, new ASIMs will be available in about one year from this writing that will be dramatically smaller (2 cm^2 vs 25 cm^2) and lower in power consumption (100mW vs. 1200 mW). We have already prototyped a simpler ASIM (based on the Atmel AT90 microcontroller) that is more optimized for operation within the CubeSat constaints (though not yet miniaturized). Unfortunately, since the AT90 is a COTS solution, we will need to perform additional work to establish a space-qualifiable version of the miniaturized ASIM. We have identified two parallel paths, the first being to "test and fix" the AT90-based

ASIM using radiation sources to test and identify weaknesses that would be corrected through redesign. The second path involves a more studied approach in which we develop intellectual property and migrate it into a radiation-hardened form (this has traditionally been referred to as “doing things the right way”), which is more optimal but more costly. We are also working to develop C&DH and radio modules as 1×1 NMF facets. The new C&DH design will integrate the same processor functionality (especially the ability to run SDM), replacing the 1×2 NMF C&DH and 1×1 NMF hub facets in the concept nanosatellite with a single 1×1 NMF solution. The processor will be based on the TI OMAPS processor, which should be even more power efficient than the present PXA270 processor. We are exploring the creation of a TDRS transponder as a 1×1 NMF facet (from scratch), as well as adapting some other radio equipment used in current CubeSat designs to be “nanoSPA” compliant. Our long range goal, however, is to develop a “unified PnP radio architecture”. Conceptually, we envision a 1x1 NMF module that operates in a manner like a cellular telephone, except having ~10 independent channels or “phone numbers”. These channels would be allocated to support a number of the previously described communications modalities through ad hoc assignment protocols, which themselves could be provisioned through XTEDS and SDM.

Connectors have emerged as another challenge that we should have better anticipated. For the concept satellite work, we used an industry standard press-fit connector. While robust for single assembly operations, the connector was difficult to separate and in some cases deteriorated after a number of disconnect cycles. We will as an interim measure use 15-pin micro-D connectors, but we are continue to search for better options (such as the so-called “nano-D” connectors, which are attractive dimensionally but costly).

So far, test bypass has not been integrated into nanoSPA. Until very recently, test bypass even for PnPSat required a rack-mounted system to operate. Our team will continue to examine strategies for easily integrating test bypass into nanoSPA, ideally using the same laptop involved with other aspects of mission development / operation. Exploiting an unused channel of the previously described PnP radio architecture is an attractive possibility for achieving a wireless test bypass.

An important and elusive challenge in creating rapid systems (small or large) is developing simple and effective “configurator” design flows, consistent with the notion of a pushbutton toolflow. CubeSats offer a more constrained “universe” than larger platforms under which more rigorous studies of “instant satellite” designs are possible. One of the more significant advancements that has occurred since the concept CubeSat demonstrators is the creation of a portion of the toolflow, one that in particular helps in the automatic construction of nanoSPA components. Creating nanoSPA components is much more difficult, for example, than using them (just as it is harder to build a keyboard than to use it). In the web-based toolflow depicted in Figure 18, an XTEDS generator constructs a syntactically correct XTEDS through a menu-driven dialog that establishes the beginning step in building a nanoSPA component. This tool then exports the generated XTEDS into a second tool (within the same *web-based* integrated development environment) that builds ASIM code wrappers. This code automatically supports the appropriate handling of device calls for XTEDS services, and stubs are explicitly identified for developer code dealing with primitive transactions associated with the raw device. A similar export process occurs between the XTEDs and a SDM application wrapper generator, which greatly reduces the tedious, error-prone processes associated with producing SDM compatible programs that we “SPA-aware”.

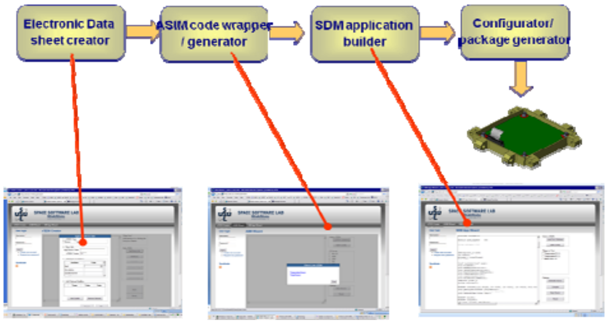

Figure 18. Web-based toolflow for creating a nanoSPA component.

The concepts described in this paper, including the more recent tools developments, have been distilled into a short course, which is being beta-tested with 15 groups this year. The course will review these concepts in a more expanded form with hands-on aids, to include entire nanoSPA networks and NMF components, along with software tools.

SUMMARY

This paper has described the first embodiment of SPA for nanosatellites (CubeSats) in particular. Many parts of this work have been prototyped in the form of three simple concept CubeSats. While much work remains, ranging from improving the infrastructural elements (miniaturization of ASIMs) to developing flight-worthy subsystems and tools, the accomplishments achieved to date are encouraging.

Acknowledgments

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