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CubeSat Launchers, ESPA-rings, and Education at the Naval Postgraduate School

James H. Newman
NASA/Johnson Space Center
NPS Code SP, Monterey, CA 93943; 831-656-2487
jhnewman@nps.edu

Daniel Sakoda
Naval Postgraduate School
NPS Code SP, Monterey, CA 93943; 831-656-3198
dsakoda@nps.edu

Rudolf Panholzer
Naval Postgraduate School
NPS Code SP, Monterey, CA 93943; 831-656-2154
rpanholzer@nps.edu

ABSTRACT

An effort is underway at the Naval Postgraduate School (NPS) to leverage its unique position as both a military research institution and a graduate university interested in educational outreach. We are working to simultaneously incorporate the use of CubeSats into our educational and space research program and to enable the access of other student-built CubeSats to DoD launches. To launch CubeSats, NPS is designing a CubeSat launcher compatible with the ESPA (EELV Secondary Payload Adaptor) interface. Through partnerships with universities and other DoD collaborators, NPS is seeking to maximize the potential for launching CubeSat payloads.

INTRODUCTION

The Naval Postgraduate School has included student-built space experiments and small satellites as part of its curriculum for many years. After several experiments were flown on the Space Shuttle, the first NPS satellite, PANSAT[1], was launched from the Space Shuttle in 1998. Currently the second satellite, NPSAT1[2], is under construction. NPSAT1 incorporates several experiments and technology demonstrations and is designed to be ESPA-compatible[3], targeting a flight provided by the DoD STP (Space Test Program). Unfortunately NPSAT1 was not ready for the recent STP-1 launch (Figure 1). Nonetheless, the educational and research value of NPSAT1 is undiminished and work continues.

Given the complexity and time required to build even a small satellite in the 100 kg class, it was realized that to ensure a continuing and robust use of satellites in the Space Systems Academic Group's (SSAG) educational and research program at NPS, an evolution to the use of CubeSats should be considered. The CubeSat is seeing growing acceptance in educational and research institutions due to its small size and relatively low cost and can provide NPS students with useful, short turnaround educational projects in satellite engineering and operations. CubeSats also show potential for use in rapid-prototyping and low-cost flight testing of advanced materials and systems and certain research payloads.

Figure 1: NPSAT1 mass simulator installed on ESPA-ring on STP-1.

Secondary payload providers typically need to build a mass simulator in the event that their payload is not ready or breaks late in test or integration. After providing such a mass simulator for the STP-1 launch, it was realized that it would be valuable to build a reconfigurable payload that could function as a mass simulator or as a secondary payload itself. Such a payload, based on the "P-Pod" launch system developed by Cal Poly[4], as shown in Figure 2, could serve either as a generic mass simulator for any ESPA payload or as a dedicated secondary payload. By packaging the P-PODs appropriately, the potential exists to launch a significant number of CubeSats.

Figure 2: Cal Poly P-POD

NPS is now working to design and eventually build and use such a payload to launch NPS CubeSats in the future. NPS is also forming partnerships with universities and other government institutions to collaborate on designs and to develop standardized manifesting and certification procedures and processes for CubeSats to be launched in such a payload. In this scenario, NPS seeks DoD-provided launch opportunities for the NPS CubeSats and serves in a liaison capacity to manifest additional CubeSats to fill the NPS CubeSat launcher. While the launcher may be manifested to a dedicated ESPA-compatible slot, it is also designed to be reconfigurable. This could permit launch on short notice in the event an ESPA slot opens up, even until late in the launch processing flow.

It is also expected that NPS students will work with university students, who will thereby also gain a better understanding of opportunities in government service. The following sections describe the NPS CubeSat Launcher (NPSCuL) and a brief description of a couple of NPS experiments that are currently being studied as CubeSat payloads.

NPS CUBESAT LAUNCHER

The ESPA-class secondary payload fits within a volume of ~61 cm x ~71 cm x ~90 cm (24.0" x 28.0" x 35.5") and contains a mass of less than ~181 kg (400. lb). The standard P-POD holds 3 CubeSats, therefore having a volume of "3U". Several P-POD launchers could be mounted within the ESPA volume and mass constraints. A configuration of ten P-PODs is shown in Figure 3 and could result in a launch of a total of 30U, where 1U is a single CubeSat and 2U and 3U are double and triple CubeSats, respectively. Cal Poly[5] has also suggested that a larger P-POD could be built, a 5U P-POD, permitting some combination up to 50U of CubeSats to be deployed. Other CubeSat form factors are also being considered. NASA/Ames Research Center is also looking at the utility of both a 2x3U CubeSat, referred to as a "six-pack", and a 4U configuration.

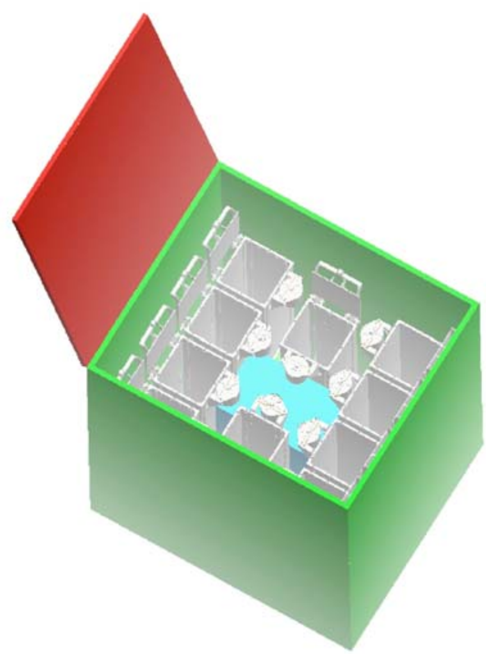

Figure 3: NPSCuL with 10 P-POD's (show better view on white background).

An NPS officer student is currently developing a simple set of NPSCuL requirements and an NPSCuL Payload Planner's Guide to describe NPSCuL and guide potential users. Table 1 shows an outline of payload user requirements.

Table 1: NPSCuL Payload Requirements

Requirement	Description
1.	Meet all P-POD requirements
2.	Ensure non-operability during launch
3.	No hazardous materials
4.	No pressure vessels
5.	Meet documentation delivery schedule
6.	Meet random vibration specification
7.	Meet static loads of 15 g in each axis
8.	Meet no-access period of 30 days (min.) until on-orbit
9.	No radio frequency emissions until 300 sec after separation

DESIGN REQUIREMENTS

Design requirements for the NPSCuL are two-fold. The first set of requirements deals with an ESPA-class payload, defining the functional specification as well as those specifications the NPSCuL must meet as a secondary payload, i.e., safety and compatibility. The second set of requirements adds a layer of complexity to allow for the NPSCuL to function as a mass simulator replacement for an arbitrary ESPA-class payload. The NPSCuL must be mass-reconfigurable to match the weight and center-of-mass of any ESPA-class payload it is intended to replace. Its inclusion on a launch manifest must not impact the overall mission.

It is important, from a structural standpoint, that the NPSCuL be designed with the worst-case scenario in mind. This implies a maximum weight and maximum center-of-mass height. The NPSCuL will have a very stiff and robust structure resulting in a high fundamental frequency. The engineering trade is in the transmittance of dynamic energy to the on-board electronics, specifically, the CubeSat payloads. Table 2 depicts some of the top-level requirements for the loaded NPSCuL. The design considers a range of potential ESPA-class payloads from 45 kg (100 lbs) to the full 181 kg (400 lbs) with a center-of-mass ranging from 25.4 cm (10 in.) to 50.8 cm (20 in.) from the launch vehicle interface.

An overall goal is to deploy the maximum number of CubeSats while maintaining flexibility for the flight configuration to perform as a standby mass simulator. In the minimum configuration of 45 kg and center-of-mass at 25 cm above the mating interface, two 3U P-PODs can be accommodated, or a 6U volume of CubeSats. More volume could be obtained by optimizing the structure for the different possible NPSCuL masses. However, to optimize the NPSCuL structure for the minimum weight would require re-designing the NPSCuL structure for a heavier configuration. This would lose the benefits of a 'standard' structure. So, in maximizing the number of P-PODs on NPSCuL, the goal is to ensure the load-bearing structure and electronics remains the same for all configurations. P-POD units, with ballast as required, will then be added to increase weight to meet the required configuration.

Table 2: NPSCuL Design Requirements.

Parameter	Value
Mass (max.):	181.4 kg [400. lbs]
Mass (min.):	45.4 kg [100. lbs]
Center-of-Mass (max.):	50.8 cm [20. in.] above mating surface
Center-of-Mass (min.):	25.4 cm [10. in.]
Limit Loads:	8.48 g each axis
Random Vibe:	7.1 g(rms), (See Fig. 5)
Fundamental Frequency:	>50 Hz
Launch Vehicle Interface:	2-wire (min.) separation signal; Optional 2-wire serial telemetry interface
P-POD Deploy Command:	Controlled Sequence, triple-redundant activation

DESIGN & ANALYSIS

The current concept of the NPSCuL design is to accommodate ten P-PODs. Total weight for this configuration is approximately 87 kg (192 lbs) before adding ballast. A minimal configuration of two 3U P-PODs would just meet the 45 kg (100 lbs) mass. Table 3 shows an estimate of the mass budget for the minimal and maximum configurations.

It should be noted that flexibility in mounting the P-PODs allows for some center-of-mass movement in the longitudinal direction. To meet a maximum ESPA-class payload, ballast would be required.

Table 3: Mass Budget Estimate

	Minimum (2 P-PODs) (kg)	Maximum (10 P-PODs) (kg)
Structure	27	27
Electronics/Cabling	5	5
Batteries	2	2
3U P-PODs (loaded with 1 kg CubeSats)	11	53
Total:	45	87

Mechanical

The mechanical design of the NPSCuL is largely driven by the ESPA Payload Planner's Guide for the mechanical interface, loads, and dynamics. Although the static loads requirement of 15 g in each axis is high, the structural dynamics requirement of >50 Hz imposes the greater challenge. It should be noted that the ESPA Payload Planner's Guide states a 35 Hz minimum fundamental frequency. However, experience has shown that all players involved, and especially the launch vehicle and primary payload providers, are much more comfortable when the secondary payloads exhibit a higher natural frequency. Intuitively this means the base of the NPSCuL must be very stiff to accommodate both the maximum mass and highest center-of-mass. Local bending modes can easily be stiffened, however, the overall rocking mode (cantilevered mounting) of the NPSCuL is dependent on the base plate stiffness.

A simple finite element model of the load-bearing structure was generated to investigate the NPSCuL dynamics using a ball-clamp boundary condition at the base. The ball-clamp restraint was applied to the lower, circumferential edge of the interface flange. A lumped-mass element was used to simulate the bulk of the NPSCuL mass for the maximum configuration. Figure 4 shows the preliminary dynamic analysis results. The fundamental frequency is 62 Hz, well above the 50 Hz minimum. However, the base plate thickness is 2.54 cm (1.0 in.) and the flange that mates to the launch vehicle interface is 1.27 cm (0.50 in.) thick.

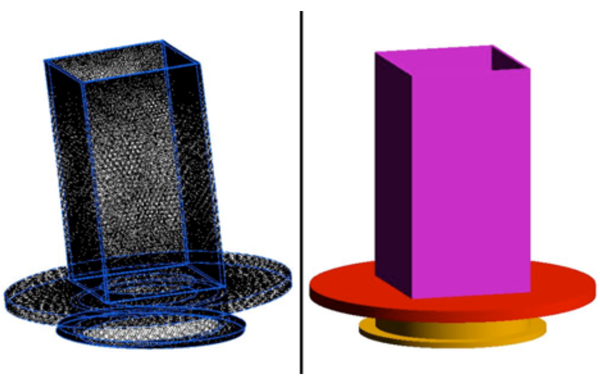

Figure 4: Preliminary Dynamic Analysis Results.

Electrical

The minimum required electrical interface between the NPSCuL and the launch vehicle is for initiation of the deployment sequence. This would be a pair of wires identical to that for a typical separation system. If the launcher is manifested as a standalone payload, optional interfaces would be requested to allow for NPSCuL battery charging and telemetry back to the launch vehicle. The telemetry return to the launch vehicle requires only a twisted pair of wires for serial communications. This could also be used as an additional inhibit where an 'enable' signal is sent to the NPSCuL to reset an inhibit relay that would otherwise disallow initiation of the P-POD actuators.

The NPSCuL electronics would consist of a micro-controller logic board, an analog board for power switching and battery charging, batteries for energy storage, and the cabling harness to connect to both the launch vehicle and the P-PODs. Figure 5 depicts a block diagram of the NPSCuL electronics. Battery charging would normally be complete before launcher integration onto the launch carrier. No pad operations are envisioned.

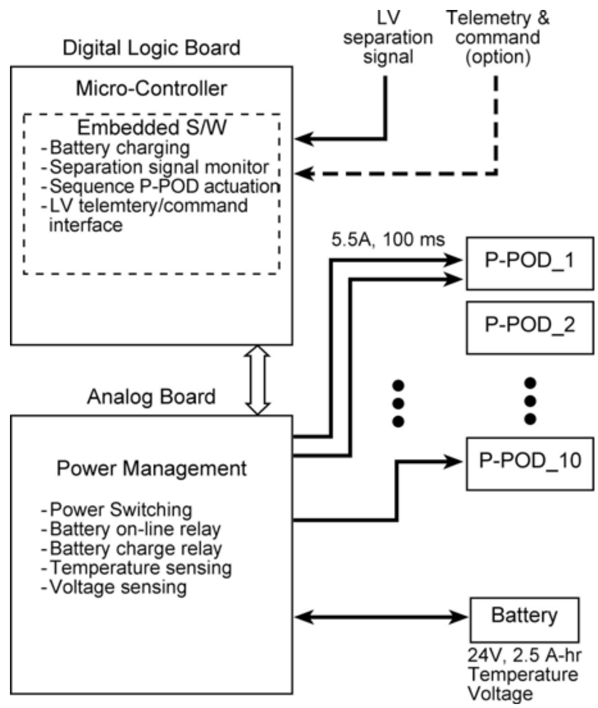

Figure 5: NPSCuL Block Diagram.

System safety

The NPSCuL will be designed to meet or exceed compliance with all potential safety requirements. Payload safety requirements are crafted for the specific launch range although the overall philosophies are identical. The NPSCuL payload safety design goal is to exceed all safety requirements to ensure compatibility with any launch vehicle and any potential manifest. This of course imposes restrictions on the CubeSat payload community but these restrictions do not differ from those promulgated through the P-POD Interface Control Document (ICD)[6]. Specifically, all CubeSats must be non-functional until after release, no hazardous materials may be used, no pressure vessels are allowed, and rigorous testing is performed on all flight units.

Environmental test

The NPSCuL will undergo full qualification testing for static loads, random vibration, and thermal-vacuum cycling. A prototype NPSCuL will be developed and tested for static loads to 15 g in each axis (factor of safety of 1.77), and random vibration testing to qualification levels as shown in Figure 6. The prototype NPSCuL will also be used to determine and envelope the worst-case random vibration spectra for the CubeSat payloads. Once the NPSCuL is flight qualified in its worst-case configuration, flight units can be tested to acceptance levels. This will be done at NPS for vibration and thermal-vacuum testing. It is planned that some NPS facilities such as a shaker and thermal-vacuum chamber would also be made available to the CubeSat community.

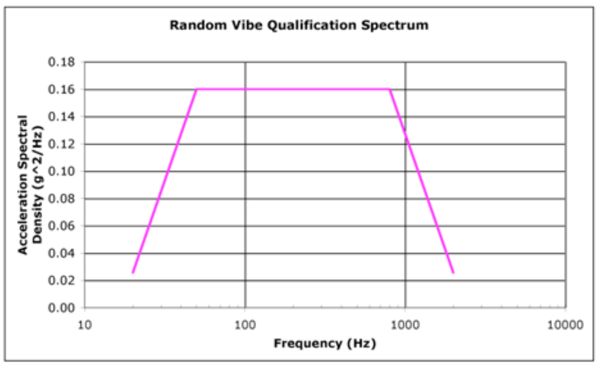

Figure 6: Vibration Spectrum.

EDUCATION AT NPS AND CUBESAT EXPERIMENTS

The students at NPS are typically United States mid-career military officers and government employees. But there are also government and military employees from more than fifty countries around the world taking classes at NPS. The students in the Space Systems curricula attend classes ranging from space fundamentals to advanced mission design courses. An experience tour of national space facilities is included during the second year and a research thesis must also be completed. A number of students are currently working on the NPSAT1 project, including building the ground station, building and certifying the Li-ion batteries, assembling the solar panels, and characterizing the MEMS rate sensors to be used in an on-orbit, attitude control experiment. And the expertise gained by the staff during the design, construction, and building of PANSAT and NPSAT1 apply directly to CubeSats.

A recent satellite design course at NPS used a 5U CubeSat form factor with a payload designed to track ships around the world using AIS (automated identification system) broadcasts. It is expected that CubeSats will soon be built based on ideas and specifications developed during NPS student design projects.

As a practical matter, one of the NPSAT1 experiments is an advanced solar cell testing capability and the first NPS CubeSat may be dedicated to performing advanced solar cell testing. NPSAST (NPS Advanced Solar Cell Tester) would be a proof-of-concept that could provide a relatively quick look at new solar cells in the space environment. The power budget for a 1U or 2U NPSAST, including the experiment, could be as shown in Table 4, with a system block diagram as shown in Figure 7.

Table 4: NPSAST Power Budget

Subsystem	Power required (mW)	Duty cycle	Average power used (mW)
C&DH	200	100%	200
EPS (Li-ion)	120	100%	120
ACS (B-dot)	120	100%	120
Receiver	100	17%	20
Transmitter (1 W EIRP)	2200	1.4% (4 passes per day)	30
Experiment	500	50%	250
Total			740

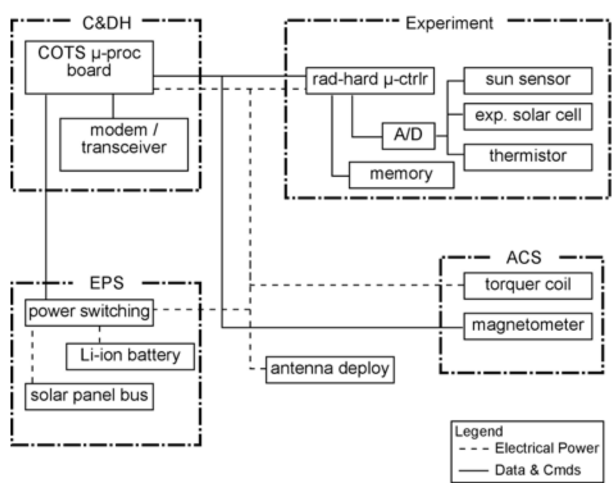

Figure 7. Solar Cell Measurement System Block Diagram.

It is also anticipated that CubeSats could be valuable in NPS laboratory courses in the future. While not all students will necessarily be interested in working extensively on specific CubeSats projects, it is possible to set up laboratory courses based on CubeSats in satellite communications and test-and-integration procedures. In addition to offering the chance to build CubeSat experiments, NPS CubeSats in orbit could someday provide planning and operations experience, thereby exposing all students at some point to real world scenarios in dealing with satellite hardware, software, and operations.

CONCLUSION

Space Systems students are exposed to numerous opportunities to implement course lessons and become familiar with real processes and real procedures if their educational curriculum includes building, testing, and operating satellites. Such skills are essential for those managing successful satellite programs. The SSAG at NPS is excited about the educational and research possibilities in satellites of the CubeSat class.

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