The Open Prototype for Educational NanoSats: Fixing the Other Side of the Small Satellite Cost Equation

Josh Berk
Department of Space Studies
University of North Dakota
4149 University Ave, Stop 9008
Grand Forks, ND 58202-9008
+1-650-229-8721
josh.berk@my.und.edu

Jeremy Straub
Department of Computer Science
University of North Dakota
3950 Campus Road, Stop 9015
Grand Forks, ND 58202-9015
+1-701-777-4107
jeremy.straub@my.und.edu

David Whalen
Department of Space Studies
University of North Dakota
4149 University Ave, Stop 9008
Grand Forks, ND 58202-9008
+1-701-777-3558
whalen@space.edu

Abstract—**Government supported nano-satellite launch programs and emerging commercial small satellite launch services are reducing the cost of access to space for educational and other CubeSat projects. The cost and complexity of designing and building these satellites remains a vexing complication for many would be CubeSat aspirants. The Open Prototype for Educational NanoSats (OPEN), a proposed nano-satellite development platform, is described in this paper. OPEN endeavors to reduce the costs and risks associated with educational, government and commercial nano-satellite development. OPEN provides free and publicly available plans for building, testing and operating a versatile, low-cost satellite, based on the standardized CubeSat form-factor. OPEN consists of public-domain educational reference plans, complete with engineering schematics, CAD files, construction and test instructions as well as ancillary reference materials relevant to satellite building and operation. By making the plan, to produce a small but capable spacecraft freely available, OPEN seeks to lower the barriers to access on the other side (non-launch costs) of the satellite cost equation.**

Table of Contents

1. Introduction

The cost equation governing the development and deployment of earth orbiting small satellite systems is given by the sum of hardware and software research and development costs, the regulatory, and integration costs as well as space launch expenses. In recent years the launch cost for commercial payloads has seen a precipitous decline in prices as new domestic and foreign aspirants are "exerting downward price pressure on traditional launch-vehicle manufacturers" [1]. As the cost to launch a payload into orbit declines, little measurable progress has been made at reducing the other half of the small satellite cost equation.

It is no secret that designing equipment for use in space has been and continues to be an expensive and complicated undertaking. In the few decades humanity has been exploiting the benefits space technologies, little progress has been made at reducing the associated development costs. Governments or companies seeking to develop space hardware often design custom, one of a kind systems to meet the demands of a specific application. This application-specific development regime has contributed to several very successful commercial and governmental enterprises but has restricted access to space to institutions that can afford the high costs associated with high-performance technology development. The unique aspects and design nuances of each spacecraft are a significant cost driver as is complying with regulatory statutes and paying for integration services.

The Open Prototype for Educational NanoSats (OPEN) is a program under development at the University of North Dakota that will build on the success of the CubeSat movement by lowering the technical and financial barriers needed for initiating a small-satellite program. OPEN is a collection of public domain resources that includes all of the documentation, schematics and other reference material needed to build a modest but capable CubeSat. By using the OPEN plans, adopters can produce a useful satellite will less time consuming research and development. This standardization and known-good-reference configurations may contribute to lower regulatory compliance costs under the recently amended ITAR regime.

OPEN presents an opportunity to cultivate a space marketplace predicated on standardized, low-cost and relatively easy to manufacture nano-satellites. This platform is poised to reduce the cost and complexity of initiating a research of educational space program while simultaneously encouraging creativity and ingenuity of its users. Through a

978-1-4673-1813-6/13/$31.00 ©2013 IEEE

confluence of factors, including providing known-working technical specifications, standardization and educational material, OPEN will decrease many of the cost drivers currently associated with educational and commercial small satellite development and operations.

2. BACKGROUND

The space age began in the waning years of the 1950's as a contest between dueling superpowers to orbit the world's first artificial satellites. Sputnik 1 and Explorer 1, the first Soviet and American satellites, each had a mass of less than 100 kg [2, 3]. In the years that followed, the average mass of satellite systems has steadily increased with the average satellite mass reaching over 4,000 kg (based on the average during the last 8 years) [4]. Generally, as mass increases, spacecraft development and launch cost swell also. Recognizing this trend and the need to educate future aerospace engineers, Bob Twiggs and Jordi Puig-Suari collaborated to develop a standardized 10 cm x 10 cm x 10 cm satellite form-factor commonly referred to as a CubeSat [5]. CubeSats provide students with a hands-on opportunity to work with and operate actual spacecraft hardware. The skills developed while working with CubeSat hardware are applicable to larger spacecraft development projects, such as those prevalent in industry and government. CubeSats also provide an opportunity for testing innovative new technologies that are not at a mature technological readiness level suitable for incorporation in a higher-risk, higher-cost mission [6, 7].

For these reasons, CubeSats have become a popular educational and research satellite platform. The small size of CubeSats generally has meant lower production costs, shorter development timelines and less project complexity. These qualities, in combination, make for a potent educational, science and technology development platform that is attractive for many different users. The National Aeronautics and Space Administration (NASA), Department of Defence (DoD), commercial and educational institutions have all experimented with CubeSats [8].

While a large satellite may incur launch expenses (as a primary payload), on average, of $99 million, CubeSats face a dramatically lower launch cost. The cost paid per kilogram on the commercial launch vehicle, Pegasus, made by Orbital Sciences Corp., is around $30,000. The cost paid per kilogram on a converted Soviet ICBM Dnepr rocket is $3,000 [9]. Emerging launch providers appear poised to offer a greater number of low-cost, competitive launch solutions. CubeSat launch costs may, in the near future, be as low as $10,000 for a 1 kg spacecraft [10]. Alternately, government programs (such as NASA's ELaNa) make low or no-cost launches available, on a secondary-space-available basis, to qualified institutions.

Initial development costs approximately $250,000, based on in-house design, development, fabrication and testing using a combination of paid and volunteer student labor [10]. The entry of commercial venders has reduced the cost of a single mission significantly. A robust kit, currently available from the Tyvak Nano-Satellite Systems Company for about $42,000, contains all required supporting subsystems and requires only independent development and integration of the payload elements [11]. These kits are, for some users, cost-effective on a single mission basis, however they tend to increase costs over multiple missions due to recurring payments for vender-incurred research, development, testing and engineering (RDT&E) expenses above and beyond the actual value of the hardware purchased.

3. VALUE OF NANO-SATELLITE FORM-FACTOR

Building a tightly coupled miniaturized satellite can be a challenging proposition for even seasoned aerospace engineers. This challenge is even greater for first time space researchers and students. These groups however can still make meaningful contributions to the advancement of space science and technology if empowered with the right kit of tools. OPEN can function as this tool kit, adding several sources of value to the CubeSat form-factor.

Low-Cost Test Platform

OPEN will provide a low-cost, low-risk test platform for sensors, actuators, propulsions systems and other technology test and demonstration needs. By substantially reducing the costs associated with a technology failure (including one that results in spacecraft lost), higher-risk technologies can be tested leading to greater innovation and enhanced results.

Capability to Mature Technical Readiness of Experimental Space Technologies

Using the existing government and commercial launch infrastructure, the OPEN platform can be used to buy-down mission risk at a lower price than indigenous design and many commercial vendor acquisition options. Missions based on the OPEN architecture can be used to advance technology readiness levels (TRL) to maturity.

In spaceflight hardware development TRLs are indexed from 1-9 as a relative measure of a systems maturity with each number corresponding to a specific level of development progress [12]. Due to mismatches in funding, providing research dollars to specific segments in the TRL ladder, gaps exist where many promising space technologies are not advanced to the next level of preparedness.

OPEN CubeSats may remove barriers for integrating experimental technologies into a free flying space platform by allowing low-cost testing in the relevant operational environment. Experimental technologies that can be miniaturized or are already small enough to fit in a CubeSat can be tested in space relatively inexpensively. In this way, both technologist and federal funding agencies are able to get a greater return on their R&D spending through a test platform that can verify the characteristics and performance of mid-level TRL projects.

Commercial CubeSat kits are presently available to use for TRL advancement but OPEN CubeSats offer several advantages particularly in application where multiple spacecraft are required. Because OPEN can be reproduced in quantity, without recurring the RDT&E expenses built into commercial kit pricing, it is advantageous for technologists experimenting with satellite constellations or scientific investigations requiring multiple spacecraft. Re-engineering commercial kits (if possible) may also create interoperability or performance issues, especially if vendors do not supply low-level hardware and software documentation. The extensive library of resources available to OPEN users, coupled with open-source software and prospectively a large user community, encourages non-traditional space developers to build and fly innovative new technologies.

Ecosystem of Innovation

A low-cost, low-risk and versatile development platform, invites OPEN adaptors to experiment with innovative and advanced technologies. OPEN encourages new development by freeing CubeSat programs to focus their resources on payloads and targeted subsystem innovation. The propensity for customization on each OPEN satellite may increase the total depth and breath of capabilities possible in the nano-satellite form-factor. As new technologies are successfully demonstrated an ecosystem of innovation may emerge.

Popular mobile phone manufacturers have leveraged a similar development paradigm popularly called crowd-sourced innovation. Here, a community of software developers has evolved organically generated new and novel software products for use on low-cost, ubiquitous hardware. Millions of new and first time software developers have emerged, generating a vibrant software marketplace [13].

Not unlike the mobile phone 'app' ecosystem, OPEN is a development platform that is scalable from low budget first-time space operations to serious space programs performing meaningful technology and science investigations. Using integrated development and operational resources, OPEN adopters can initiate a space program without prior experience working with spaceflight hardware. Though expertise in the relevant engineering domains is of course required. OPEN represents an opportunity to capture new spaceflight developers who may be attracted by the low-barrier to entry and the possibility of doing something new and profoundly interesting in outer space.

4. Technical Overview of the OPEN Framework

The OPEN design (shown in Figure 1) is comprised of a top and bottom plate, four vertical corner support bars (which also serve as the point of contact with the P-POD), an interior structure for supporting the payload elements in the payload bay and four printed circuit boards (PCBs). The PCBs are inserted into the spacecraft vertically (up/down the z axis) and are held in place by the corner braces. The PCBs also provide structural rigidity to the spacecraft. Figure 2 shows the form factor for the board, which extends the spacecraft's volume into the 0.6 cm of overhang area available on four sides of the spacecraft (according to the P-POD integration specifications [14]). Utilization of the overhang area increases the volume of the spacecraft by approximately 30% [15]. The PCBs utilize a modified version of the PC/104 specification, which has been adapted to fit within the allocated area and to support the vertical insertion method. A diagram of this board configuration is shown in Figure 3.

5. Assessment of OPEN's Ability to Deliver on Projected Sources of Value

A basic cost estimating model for an OPEN barebones CubeSat is included below. This configuration is defined as a modest 10 cm x 10 cm x 10 cm spacecraft which utilizes the P-POD overhang space, as depicted in Figure 1, with basic attitude control and communications capabilities [14]. The estimate includes rough-order approximations for materials only. Not included are the tools, software, development kits, facilities and equipment expenses or other resources that may be required to assemble the spacecraft. These expenses are non-recurring costs and are considered facilities investments that are beyond the scope of this evaluation.

By utilizing COTS hardware, including electronic components and materials not originally designed for spaceflight, OPEN is projected to have lower development expenses, compared to retail CubeSat hardware. This will help facilitate the development of a CubeSat with an aggregate component cost below $5,000. Tests conducted in orbit by the OpenOrbiter spacecraft, will establish the benchmark performance for the included economy hardware.

Structure

The primary structural elements of the spacecraft are, as required by P-POD instigation guidelines, manufactured from aircraft grade 7075 aluminum metal [14]. This structure consists of four corner posts and two plates (at the top and bottom) of the satellite. This aluminum material is available from a multitude of metal suppliers including local and online vendors. The requisite material can be procured for a few tens of dollars.

Attitude Determination and Control System

The Attitude Determination and Control System (ADCS) system is responsible for integrating sensor data to calculate spacecraft orientation. From this data the ADCS uses reaction wheels to stabilize and orient the spacecraft. This system is a vital, yet an inexpensive system when assembled from components readily available at electronic parts supply stores. The ADCS system consists fundamentally of three small reaction motors, independent motor controllers, and magotometer and gyroscopes for attitude determination.

The price for three (11.12 mm x 5 mm x 5 mm DC micro motors) is approximately $4.50 [16]. These constant spin motors are capable of providing sufficient reaction force to stabilize the spacecraft and perform rough pointing attitude control. Independent control of each reaction wheel is accomplished via two serial motor controllers managed by the onboard flight computer system. The cost of these circuits is $49.90 [17]. Sensor data on spacecraft attitude will be collected by a Tri-Axis solid-state gyroscope. The L3G4200D gyroscope sensor has a retail cost of $49.95

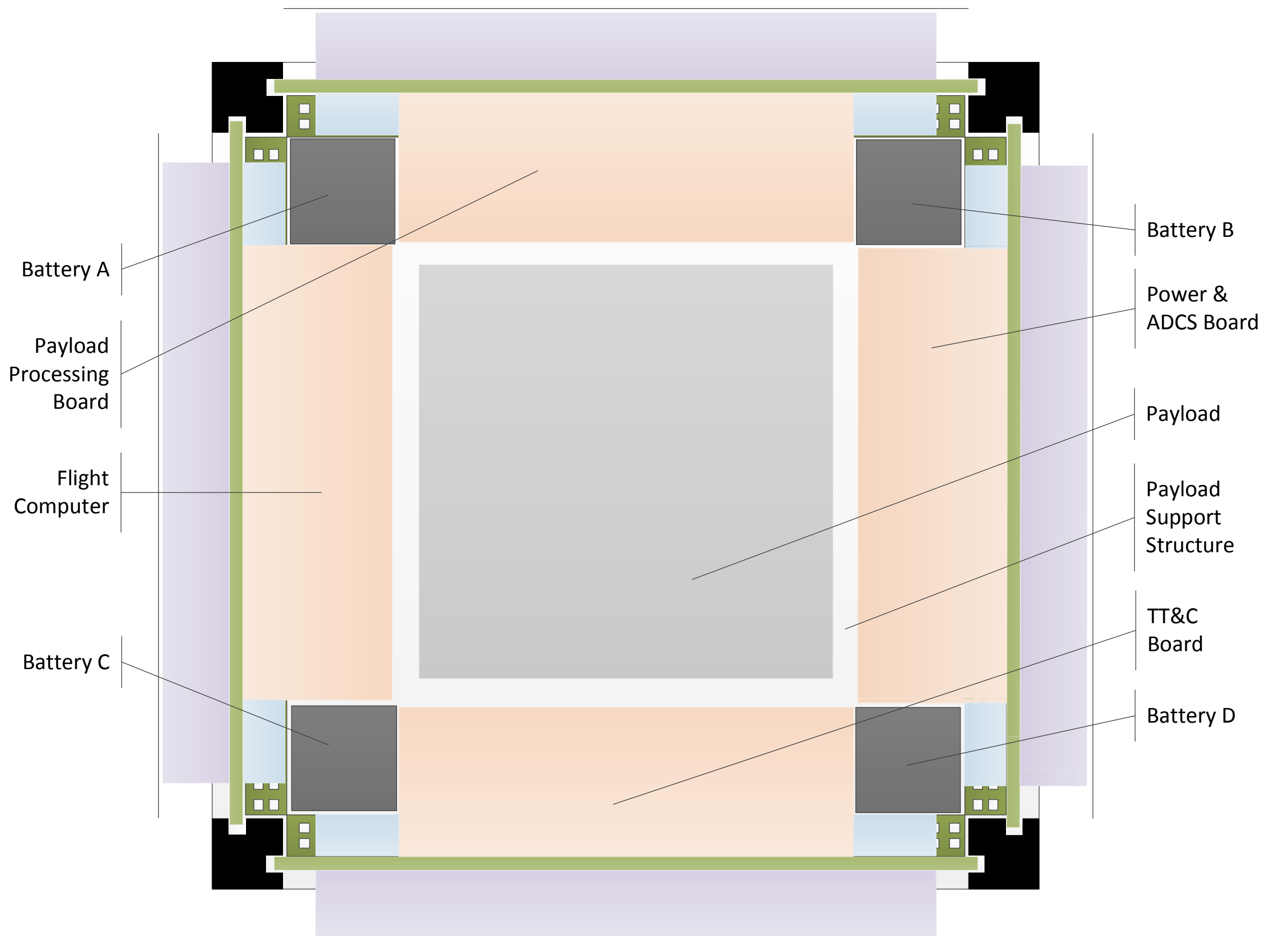


Figure 1 – OPEN Layout [15]

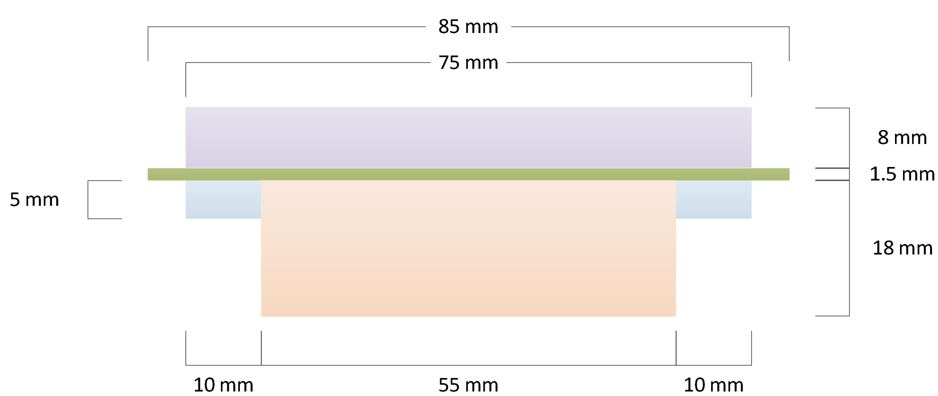


Figure 2 – OPEN Board Configuration [15]

[18]. To provide the ADCS computerized management software additional locational data, the HMC6343 magnetometer was selected to sense the spacecraft orientation relative to the Earth magnetic field. This component carries a $149.95 cost [19].

Onboard Processing

The onboard computers perform the vital task of coordinating and managing all spacecraft functions. The computers chosen for use the OPEN satellite base configuration includes the Raspberry Pi and the Gumstix computer-on-module. These systems were chosen because of their small physical dimensions, low-power requirements and relatively powerful performance. These computers are also exceptionally low cost. A Raspberry Pi computer costs $35 while the more powerful (1600 versus 800 DMIPS) Gumstix COM has a retail cost of $139 [20, 21].

The Rasberry Pi will serve as the always-living flight computer. Four Gumstix WaterSTORM COM units will be utilized on an as-needed basis for payload data processing [22]. The payload processing COMs will only be powered on when being utilized.

Electrical Power System

The electrical power system includes three critical elements. The spacecraft must have solar panels for capturing electrical energy, batteries for storing that energy and control circuits [23] to regulate power flow and control battery charging. The interaction of these systems is monitored and actively controlled by the onboard flight computer in response to real-time sensor feedback and astrodynamic positioning information [24].

Current estimates for solar panels sourced from Spectrolab Inc are space qualified and can be assembled into an array to provide sufficient energy generating capacity to trickle charge the onboard battery storage system. The cost for a bulk supply of these cells, enough to meet the energy generating needs of an OPEN spacecraft is $250 [25].

Battery costs are estimated to cost $95.88 based on a power storage system consisting of 12, 3.3v, Tenergy RCR123A, Lithium Ion batteries [26]. Wired in parallel this system will store 1080mAH of electrical power. The batteries are space qualified and their throughput is advertised to perform nominally for 500 duty cycles.

The prototype of a voltage regulation and distribution circuit has been developed. The cost for this board was approximately $75 [23]. It is estimated the addition of a charging and batter management system as part of an active battery control network will cost an additional $25.

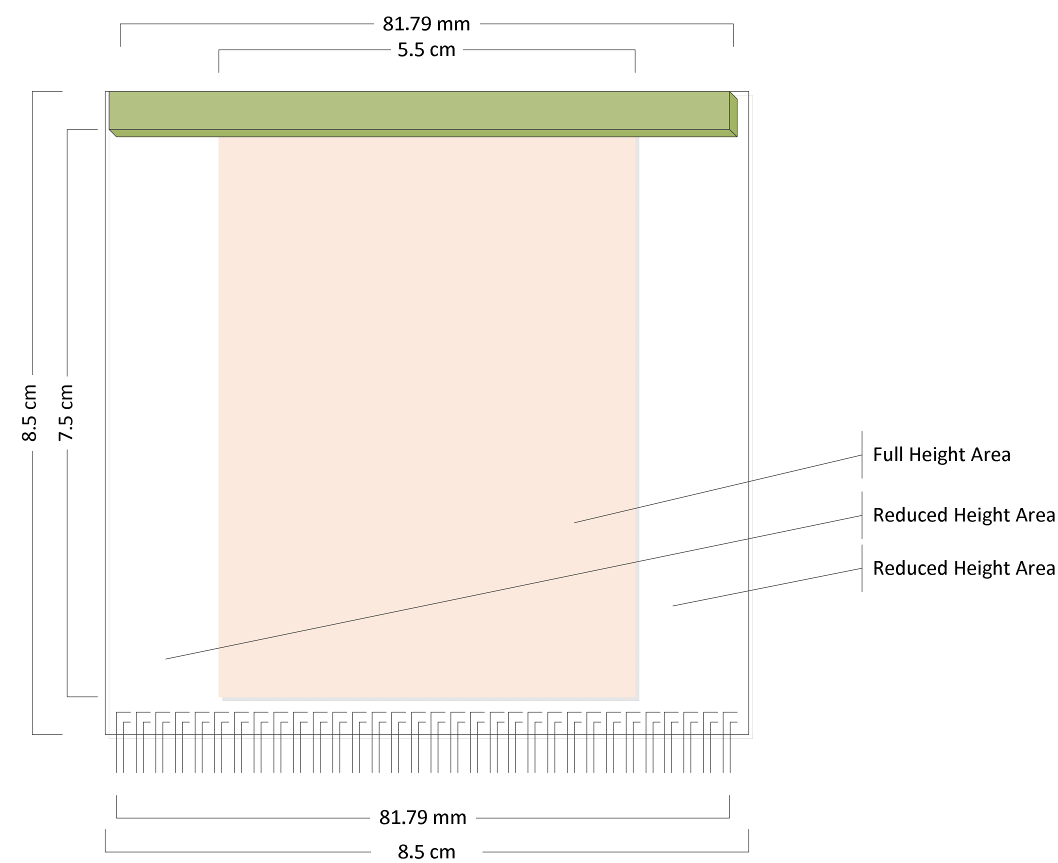


Figure 3 – Diagram of OPEN Board Specifications [15]

Radio

The radio handles outgoing and incoming communications that allow operators to issue spacecraft instructions and receive telemetry and payload data. The OPEN radio, which is based on a communications system designed by students at the California Polytechnic State University at San Luis Obispo (CalPoly), features a reliable low-cost design [27]. Due to inability for most non-governmental organizations to access a global communications network, the OPEN radio will be designed to transmit and receive in short bursts, while orbiting over a specific ground station. The radio will be built from common electronics parts, (such as programmable micro controllers, transmitters etc.) and will use the armature radio AX.25 data packet transmission standard to handle telemetry uplink and downlink.

Reducing the complexity of the communications system will save on cost and help to minimize mass and volume requirements. For this reason the OPEN radio will implement a Terminal Node Controller based on software not dedicated hardware. This basic architecture has demonstrated reliable and dependable by Cal Poly using parts not costing more than $137 [27].

Thermal Subsystem

Maintaining thermal operating conditions within the operational bounds of other subsystem components is the job of the thermal subsystem. The OPEN design relies on a very simple and inexpensive passive thermal control system for regulating the internal thermal operating environment. Kapton tape, a low mass and relatively inexpensive tape can be used as both an insulator and to reflect incoming solar energy. A role of Kapton tape can be acquired with sufficient quantity to build multiple OPEN spacecraft for under $150 [28].

Summary

With a management reserve of $500, the component hardware for an OPEN spacecraft can thus be obtained for less than $5,000. Table 1 depicts a high-level budgetary breakdown for an OPEN-style 1-U CubeSat. For CubeSat programs of the past, managers had to make the tough choice between indigenous design to save money or purchasing expensive retail components to save time. OPEN is a game changing opportunity for educational and other would-be space programs to build a very low-cost spacecraft without incurring a penalty for the time it takes an organization to assemble and program a machine of such complexity.

6. CURRENT CHALLENGES

Technical Expertise

In spite of the comparatively small scale of a CubeSat project, the design for one of these spacecraft (e.g., a 1-2 unit CubeSat) requires several integrated and mutually dependent elements. For a mission to be successful, it is critical that all of these elements work independently and cooperatively.

Table 1. Cost breakdown by category.

Category	Cost
Frame, material and fabrication	$50.00
Motors	$4.50
Gyrosope	$49.95
Motor Controllers	$49.90
Magnotometer	$149.95
Power, condition and charging	$100.00
Batteries	$95.88
Photovaltaic Panels	$250.00
Radio	$137.00
Onboard processing (4 Gumstix)	$556.00
Onboard processing (Raspberrry Pi)	$35.00
Thermal subsystems	$148.00
PCB fabrication	$850.00
Mechanical fabrication budget	$600.00
Miscellaneous	$900.00
Management reserve	$500.00
Total	**$4,476.18**

For programs just getting started, the technical challenges required to implement a successful CubeSat program are numerous. Many colleges and universities lack faculty with the adequate technical knowledge in one or more areas, or have an incomplete understanding for how discipline specific knowledge can be applied to the challenge of designing and constructing an integrated spacecraft. Large universities where all of the necessary disciplines are represented still may have knowledge gaps where the subtleties and complexities of spaceflight operation are not fully appreciated.

Some institutions may choose to resolve this issue by purchasing commercial off the shelf (COTS) components to simplify the design process. Spacecraft assembled from COTS loses some of the educational benefits to team participants whose field of experience is sidestepped by purchasing a ready-to-integrate subsystem. A secondary concern when substituting indigenous design for COTS hardware is the added design cost.

OPEN provides both the educational and design resources (CAD files, design documents, etc.) needed to build a working spacecraft bus. In learning about the hardware and software elements, students building an OPEN satellite gain experience in both theoretical and applied design. And since OPEN is inherently supportive of user modification, enhancement and customization, students don't loose out on the opportunity to contribute meaningfully to the design process. OPEN is a powerful educational platform that can be leveraged by educators to teach STEM principles and invite creative thinking. OPEN lowers technical experience barriers to entry while preserving the rich educational experience that the CubeSat genesis initiated.

Hardware Design Costs

The hardware design process for a CubeSat-class spacecraft is a multi-stage iterative process with many interdependent elements. This process begins with high-level design work which must be refined to conform with technical, fiscal and other constraints. The process may require several iterations of substantive changes to fix latent issues that are not fully realized until reviewed in totality. Starting from publically available technical resources, the design, development, fabrication and testing process for some CubeSat projects has reached $250,000 [10]. The largest component of this cost is the labor that is involved. Having a known-good technical reference will reduce development time and expense. It will also free the spacecraft design team to focus their resources on the particular components that are the prime elements of the mission's investigation.

Test and Integration Costs

The National Research Council report [29] notes that 75% of cost growth occurs after the critical design review (CDR) milestone. Further, they indicate that the "highest percentage of schedule growth" occurs subsequent to the start of the testing and integration phase. Test and integration costs, thus, must be considered as consisting of two parts: costs of testing and integration and remediation costs. The Student Qualitative Undertaking Involvement Risk Model (SQUIRM) [30], a risk assessment approach for student-involved research projects, enumerates the multitude of prospective occurrences that can impair a project. Given the aforementioned, testing, integration and the associated remediation activities required to repair components that are mal-designed, miss-fabricated or damaged throughout the integration and testing process should not be understated. A few key aspects of the SQUIRM Model deserve particular attention, in this context. These include the potential failure, attributable to inexperience and other causes, to develop a comprehensive testing plan for a given system and the potential failure to properly implement it (or even realize that it is not being implemented properly).

While it is not asserted that OPEN is a panacea to small spacecraft integration and testing problems, the test plan development is one area of prospective contribution. By creating a publically available and comprehensive test plan document, the potential for inadvertent exclusion of critical testing is reduced. This plan can be refined by the developer community, should additional types of testing be found to be required. This approach is not unlike the way the FAA responds to aircraft technical failures through the creation of new testing and remediation requirements for specific models of aircraft.

It has been suggested [31] that providing this type of test plan could lead to developer over confidence, based on an inaccurate presumption that integration and testing is "solved". It is presumed that most will see the test plan for what it is; a starting point to augment and modify the plan to account for the unique system-level testing required by each instance of an OPEN type spacecraft. Developers making subsystem or other modifications will require more extensive modification of the test plan.

End-of-Life Safety Compliance

Several regulators for small spacecraft exist. Given the need for virtually all satellites to engage in communications with Earth-based control stations (either directly or indirectly), the Federal Communications Commission (FCC) is a key regulator. In addition to licensing the communications aspects of the spacecraft, coordinating the frequency allocations with other federal agencies and foreign operators (via the International Telecommunications Union), the FCC has also been tasked with assessing the risks posed by these spacecraft to those on the Earth. Pursuant to the Outer Space Treaty of 1967, each government is responsible for damage or injury caused by its spacecraft (inclusive of spacecraft owned and operated by its nationals). The U.S. government requires spacecraft developers to submit an Orbital Debris and Risk Assessment (ODAR) document to assess this risk. For the uncontrolled reentry approach typical of CubeSats this requires an assessment of the "number of components/fragments, and their estimated dimensions and mass, likely to survive to the Earth's surface" as well as an "estimate of the probability of human casualty resulting from surviving components / fragments of the satellite" [30]. Based on analysis of this data, the operator may be required to secure an insurance policy to indemnify the U.S. Government against loss. One approach to satisfying this requirement is to use projection software developed by the National Aeronautics and Space Administration (NASA) Orbital Debris Program Office [32]. This approach requires a detailed CAD model to be supplied for analysis. From a pragmatic perspective, a similar level of assurance may be able to be provided by identifying certain 'known-safe' configurations (e.g., the spacecraft doesn't contain certain materials known to be resistant to atmospheric burn up, etc.) that can be approved without requiring this level of detailed review.

Communications Licensing

In addition to its role in assessing reentry risks, the FCC also has a (historically primary) role in authorizing the use of various communications frequencies. For a U.S. (non-governmental) satellite, an FCC license is required for both the spacecraft-based and any U.S.-located ground-based transmitters. Small satellite operators can seek this licensing under the auspices of amateur use (if applicable).

Alternately, they can seek an experimental or commercial license.

Export Control Compliance

In addition to the FCC, two other sources of regulation exist. First, the National Oceanic and Atmospheric Administration (NOAA) is responsible for the licensing of Earth-sensing satellites. Second, International Transfer of Armaments Regulations (ITAR) and Export Administration Regulations (EAR) may impact the ability to allow foreign national participation in spacecraft development efforts, limit the transfer of some information to foreign nationals, limit the ability to use foreign launch providers and necessitate the implementation of policies and procedures to effect the aforementioned.

Despite the growing prevalence of small satellite programs in the U.S., a comprehensive ITAR compliance solution is elusive (even in light of recent legislation). Universities, corporations and small businesses are caught between the requirements of inclusivity promulgated by Title 6 and 7 of the Civil Rights Act of 1964 and the requirement of exclusion of foreign nationals from access to various equipment and certain technical discussions. The broad descriptions of the types of equipment that foreign nationals may be required to be excluded from access to and discussions about makes ITAR compliance uncertain at best.

Universities, a key target of the Open Prototype for Educational NanoSats, may choose to rely on a section known as the "basic research exemption" that excludes research of "a type that is normally published" from being controlled by ITAR [33, 34]. Unfortunately, it is unclear as to the exact boundaries of this definition and this may not include access to the technical data and equipment required to actually perform the research (just to the results). An additional exemption allows universities to transfer technical data of a type that would normally be restricted to employees meeting certain requirements. This, again, is not a complete solution as it fails to include student volunteers nor does it effectively deal with the access to hardware required for research to be performed.

7. OPEN PROTOTYPE FOR EDUCATIONAL NANO-SATELLITES (OPEN)

At current launch cost levels, the hardware costs are a non-trivial category of expense. Historically, high launch costs have dwarfed minor hardware cost reductions. However, the current and projected low-cost of launch services, combined with free-to-developer launches available from NASA's ELaNa, makes hardware price reductions a key driver of mission feasibility. New entrants may find hardware development or high vendor costs as key barrier to entry. This is especially true for educational and non-profit entities who can secure a low or no-cost launch via ELaNa, the USAF or other sources. Some entrants may be unable to meet this initial cost of entry, while others may find having to re-buy the amortized cost of vendor design services a barrier to subsequent missions [35].

One way to remove the barriers to access described above is to build a spacecraft based on a comprehensive set of public domain plans. To provide maximum utility, these plans must detail every nuance of spacecraft design, development, testing and operations. This knowledge can only be fully validated by a fully executed mission. UND's OpenOrbiter spacecraft will serve as the first validation of the OPEN designs. Subsequent validation can be conducted via the community and through follow on UND missions. By placing this knowledge in the public domain, the CubeSat community is able to avoid repetitively paying amortized vendor design costs, a key driver of hardware price. The Open Prototype for Educational NanoSats (OPEN) project does just this.

To facilitate this, students and faculty at the University of North Dakota are designing, testing and promoting an open architecture for experimental and educational nanosatellites. By project completion, openly-available designs for key components (e.g., power, ADCS, bus, onboard computing, structure) will be created to facilitate broad implementation in university business, or government nano-satellite programs.

These plans can be used either unmodified or they can be adapted to support specific mission needs. By using designs that have already been shown to perform in space, risk is lessened significantly. Moreover having a known-good starting point simplifies project planning and allows a project to be implemented to focus on a single topic or subsystem. Alternatively, OPEN allows for a meaningful satellite program to be set up even if technical staff is not fully cognizant of all the engineering disciplines required to build an entire satellite from scratch. For example, an applied physicist could use the OPEN framework as a test platform for demonstrating and verifying a next generation propulsion technology.

Key OPEN program objectives include to:

- Develop a CubeSat bus and key subsystems
    - That supports a common sensor/peripheral connector/interface standard.
    - Is easily understandable and modifiable by educational, science and technology demonstration users.
    - Is compatible with and upgradable (on a sub-system basis) to space hardware vendor (COTS) components.
- Demonstrate onboard computer system based on GumStix and/or Raspberry Pi technology with operations software for all key systems.

- Create diagrams, educational reference material and other documentation to provide an entry point that facilitates low-cost missions and a gradual transition to more robust COTS or custom developed hardware to support a maturing program.

- Test the documentation to ensure that this design is construct-able by a college or university with a parts and PCB fabrication budget under $5,000.

- Document how the 1-U base design can be expanded to support craft up to 3-U in size.

Design Documentation

OPEN will include, when complete, a comprehensive set of design documents. These files will include a level of detail suitable for immediate fabrication. The design documents will include detailed electrical and mechanical schematics for all subsystems. Notably, this includes a complete UHF/VHF radio and reaction wheel-based ADCS design. To increase the utility of the hardware that may be produced based on OPEN design documents, flight control and operations software will be produced and made available under the GNU General Public License (GPL). As is typical with GPL licensed software, the source code will be made available to the user community, which is encouraged to modify it as needed. A spacecraft built according to the OPEN plans will conform to the CalPoly 1-U CubeSat specifications and P- POD integration requirements [14]. OPEN complements and builds on the success of these standards to further reduce barriers to implementing a CubeSat development program.

Assembly, Integration and Test Instructions

The documentation will include detailed step-by-step fabrication, integration and testing instructions for the base OPEN configuration. This information will be provided in written form and via digital online video. The instructions will include details of both the technical steps required (e.g., mounting components on a vendor-produced PCB) as well as guidelines to facilitate the process (e.g., a list of vendors that can provide board fabrication services). The goal of the documentation is three fold. First it serves to assist in spacecraft construction. Second, it is a reference work for students and researchers to learn about test plan design. Finally it can serve as a starting point for planning more complete products.

Test Plan

The testing of a small spacecraft is an area of particular concern. All spacecraft must be able to survive the rigors of launch and the radiation, vacuum and other characteristics of the space environment. The development of a comprehensive test plan is a time-consuming process. Further, the omission of critical elements from the test plan may result in defects or oversights remaining in the final spacecraft which are not detected until the spacecraft is on orbit, when it may be too late to resolve them. To facilitate successful completion of educational and other small satellite projects, the OPEN framework will include a comprehensive test plan for the base OPEN configuration. This will be a complete testing solution for those who are simply fabricating the spacecraft based on the plans. For those that are using the OPEN framework as a starting point for customization, the testing plan (like the design documents) will serve as a known-good starting point.

The test-plan will be sensitive to the fact that OPEN adopters may not have access to the physical facilities and test equipment used by professional satellite developers. The plan will highlight alternative testing options where available and, more importantly, explain the significance of a test, what it accomplishes and how it works. This will allow builders without access to the full spectrum of testing resources to make calculated decisions about how to satisfy testing procedures based on user specific access to testing resources and budget.

Version Control Management and Access

Initially, version control requirements are quite simplistic. A close-knit team (albeit dispersed somewhat geographically across numerous departments and their respective buildings at the University of North Dakota) is working to create the version-one release of the OPEN framework. However, like with the Linux movement, the goal of OPEN is to encourage user innovation. Given this it is necessary to have a way to merge some changes in to the base OPEN framework (meaning that they are fully supported and included in the fabrication instructions, test plans and other documents) while leaving others on the periphery to be used by programs at their own risk and without documentation support.

The GitHub service has been utilized by the software teams at UND to control the five separate development projects that comprise the OPEN and OpenOrbiter software development project. We anticipate utilizing a similar approach for version control and access management to the hardware design documents and other technical documentation. Most users will simply download the most recent consistent (called ‘stable’ generally in the Linux community) version from the website and make use of it. However, it is anticipated that some will desire to contribute their suggestions, corrections and innovations back to the project. Like with GitHub for software, there will be an area manager with responsibility for each subsection of the design and other documentation. This individual will be responsible for determining what changes will be allowed into the core design for the area. This will, of course, require significant coordination as a change to the design, for example, will generally trigger corresponding changes to assembly, test and other documentation (which all must reach a consistent point for a ‘stable’ release to occur).

Initially, these area managers will be largely from the University of North Dakota. Over time (and presuming that the community embraces the OPEN concept), it is anticipated that these roles may be dispersed across individuals at numerous participating institutions. This will, of course, pose an even greater challenge from a project management perspective. The operations of the Linux community [36] and the Java Community Process [37] will form the initial basis for the OPEN version control process.

8. ADDED VALUE OF THE OPEN PLATFORM

Accessible Design Philosophy and Scalability

The OPEN platform is a versatile testbed capable of supporting a broad range of missions. This multi-faceted capability is made possible by the adaptability and modifiability of spacecraft subsystems. Included, as an integral component of the OPEN philosophy, is extensive documentation of hardware capabilities, performance and schematics as well as complementary educational resources. These documents will help users effectively modify satellite elements to support expanded mission capabilities and scale to multi-unit CubeSat missions. Users are encouraged to develop, modify and improve the capabilities of OPEN spacecraft to match the system requirements of their mission, and to share these updates with the entire community, if desired.

Innovative Structural Design

To promote the broad utilization of the OPEN platform we propose to develop an innovative internal structural arrangement to optimize the payload volume of the minimalistic Cube Satellite form-factor. By designing all the spacecraft subsystems to fill the periphery structure of satellite we endeavor to leave space for a payload up to 5 cm x 5 cm x 10 cm and a payload board, for a total payload space of 404.5 cm^3 has been allocated [15]. Note that is space is in addition to an ADCS, computer system, radio and power subsystems.

Using this configuration users are empowered to take full advantage of a larger payload volume then is afforded by commercial subsystems of equivalent type. It is hoped that this innovative structural design will not only help popularize the OPEN standard but will also yield a wave of innovation and creativity as users are free to experiment with larger payload designs. Examples of configurations supported by this architecture include:

- Large aperture optical systems
- High bandwidth communications package
- Combination of several small payload elements
- High performance, long endurance propulsion system (for which the central payload cavity allows the propellant tank to be located at the center of mass)

Use of Inexpensive, Commercially Available Components

Fabrication of an OPEN-style spacecraft is possible using inexpensive and commercially available components. All satellite systems developed by our team will be driven by cost and performance analysis, yielding a modest, but capable spacecraft, constructible within a $5,000 budget. Because costs are one of the principal barriers preventing widespread academic utilization of the nano-satellite platform, the OPEN architecture provides an easy access point for initiating and maturing a small spacecraft program. Additionally our hardware is designed to be compatible with some commercially available subsystems. This enables would be adopters a pathway for upgrading to mission tailored systems as users gain confidence and experience working with our low cost, instructional platform.

Increased Access

Several distinct user communities will be served by the OPEN platform. All of these communities benefit from making space more accessible to students, hobbyists, scientists and others. OPEN facilitates access through reducing capital barriers to entry, potentially minimizing regulatory uncertainty and reducing the breadth and depth of technical experience needed to successfully build and validate the space-worthiness of a CubeSat. CubeSat projects which start from only engineering literature (instead of plans) must commence with an elaborate and time-consuming design process. Alternately, a vendor kit can be purchased. The former limits the ability of students to participate in a program from start to completion, the later limits student involvement and makes it less likely for students to achieve the benefit of participating in the program from initiation to conclusion. Commercial users may suffer from prohibitive capital and opportunity costs, if they pursue this approach. Purchasing some or all of the subsystems is not a panacea, as this may necessitate a cost that exceeds institutional funding mechanisms. Problematically, because a success (an orbital launch) results in the loss of access to the purchased components, these costs must be incurred for each iteration of the program. While a gradual buy-to-build transition may be possible (e.g., gradually developing in-house designs to replace vendor-purchased ones), this requires a significant outlay on vendor components (likely over several program iterations).

OPEN also facilitates access in several less tangible ways. It may provide an export control solution (which is discussed in detail in a subsequent section). The OPEN instructions also include information about programmatic concerns, such as requirements that may not be overtly apparent and licensing from the FCC and NOAA.

Increased Reliability

The OPEN increases spacecraft reliability. This is facilitated in several ways. First, OPEN includes detailed test plans for the base OpenSat design. These test plans can be used as-is for a non-modified implementation or modified for use in other configurations. Second, OpenOrbiter (a prototype OPEN-derived spacecraft being built at the University of North Dakota), will be used to space qualify the OPEN design. This will result in future OPEN adopters being able to rely on the knowledge that the design and recommended components have performed successfully in space. This reduces risk, allowing focus to be placed on user specific implementation and any changes applied to the design. Further, the higher TRL level of the base spacecraft should ease funding agency concern about the reliability of the design.

In addition to the benefits provided via the OpenOrbiter test article, additional testing may subsequently be performed via the larger community of OPEN adopters. This community review and enhancement process may, over time, evolve into a community driven version control system similar to the process with open-source software. The large number of prospective varied applications will necessitate (and thus cause) testing of the OPEN framework in a multitude of ways (some of which are not even conceivable at present).

Reduced Development Time Frames

A vendor-provided solution is, for certain applications (i.e., those that do not require any customization of the structure or key subsystems) an excellent way to reduce the production timeframe. However, if innovation is to occur in regards to one of these subsystems or innovation in another area requires modification to a standard subsystem (e.g., the ADCS must be made more robust to support a propulsion system demonstration) significant integration design, development and testing work will be required. By starting with the OPEN platform, immediate fabrication (possibly by a vendor with OPEN component fabrication experience) can be performed for applications that do not require a design modification. For applications where a modification is required (or where it is subsequently discovered that a modification is required or desirable), the base OPEN design reduces documentation and can be adapted to facilitate this. This removes the complexity and time costs as compared with designing and testing an integrate-able component from scratch.

For involved students, reduced development timelines are a critical consideration. A multi-year project will result in significant student turnover (increasing project risk), further this will act as a disincentive to student participants who are interested in seeing the launch and operation of the hardware that they have worked on in space. The OPEN framework facilitates the incorporation of CubeSat construction into a junior/senior design project or similar curriculum, allowing students to (pending launch service availability) have a more complete small satellite experience.

Reduced Development Costs

Having a known-good reference for all mechanical, electrical and software components of a CubeSat reduces the total development costs of building a reliable spacecraft. OPEN provides all of the documentation and reference material needed to fabricate discrete spacecraft elements as well as integration instructions, testing operations and procedures. Taken together this means less time, energy and resources need to be dedicated to producing functional hardware.

Purchasing satellite components from commercial vendors or even whole preassembled spacecrafts adds costs beyond the raw hardware and fabrication expenses incurred by the seller. The development of commercial spacecraft hardware requires expensive research and development. The cost for which are passed on to the consumer. A basic CubeSat has intrinsic hardware and fabrication costs perhaps as low as a few thousand dollars but COTS vendors pass their R&D expenses as significant markup. Building an OPEN-style spacecraft utilizes designs created for public use at no cost to the user. Thus, fabricating according to OPEN specifications provides a substantial savings to the end user.

Reduced Skillset and Experience

The interdisciplinary nature of spacecraft construction can be particularly problematic in a university setting. Some colleges, technical schools and universities may completely lack faculty with various technical skill sets that would be required to design and develop, from scratch, a small satellite. Other programs may suffer from a lack of interest of these key personnel. Still others may face the difficulty of justifying spending research time on a task that is inherently unpublishable (i.e., implementing a non- innovative design) and thus not aligned with faculty member promotion-driven research priorities.

By providing a complete CubeSat solution, OPEN implementers need not deal with parts of the satellite design where they are not planning to innovate. Though they still must integrate and test these components. This allows projects to be conducted with limited access to (or absence of) faculty members in various disciplines. This also allows small satellite development work to be a publishable research activity from much earlier in the process than would be otherwise possible.

Reduced Regulatory Uncertainty

Several regulatory concerns will be satisfied by the OPEN framework. First, the radio transmitter designs will be tested for compliance with FCC regulations. While testing will be required on particular implementations (that do not use a specific vendor that has had a base unit tested previously) and any changes, the known-good starting point should reduce the level of effort required for testing. Additionally, documentation will be provided as part of the test plan to guide an implementer through the testing process. Documentation will also include details on the licensing requirements and various approaches (amateur, experimental, etc.) possible.

Second, a CAD model and other details required for assessment of the spacecraft's ability to survive reentry and potentially cause injury or property damage will be provided. For those implementing the base design, this will be a complete solution that can be provided to the FCC. Any modifications will require the reevaluation of the re-entry survival projection; however, again detailed instructions will be provided as a starting point for this work.

Third, the OPEN framework aims to provide a mechanism for easing International Transfer of Armaments (ITAR) and Export Authorization Regulations (EAR) concerns. Several strategies for doing this are possible. First, the plans could be submitted to NASA or the DoD and approved for unlimited distribution. This approval means that the technical documentation falls outside the scope of ITAR and EAR control and can be distributed without restriction to foreign nationals [38]. This unlimited distribution mechanism is routinely used to clear material that could otherwise be restricted by ITAR for public release [e.g., 39, 40, 41, 42, 43, 44].

Second, a ruling could be obtained from the Directorate of Defense Trade Controls, (DDTC) such as was obtained by Bigelow Aerospace in 2010, exempting that company's inflatable space habitat from regulation [45]. While this landmark ruling was the first of its kind, it may pave the way for further ITAR easing in other cases where the DDTC perceives the potential for similar national benefit. Finally, an export approval and technical assistance agreement could be obtained.

As with any interactions with a discretionary body, the exact outcomes of each of the aforementioned cant be predicted. DDTC interpretations of recent ITAR changes may remove or severely limit this concern. Alternaticely, the may allow a nearly useless craft configuration to escape regulation while still restricting critical components (e.g. GPS hardware), making little real impact.

Recent changes to the ITAR statute, which have yet to be interpreted by the DDTC (the enforcing agency) may minimize the requirement for these compliance activities (unless a program will include nationals from specifically designated countries).

No assertion is made that any of the foregoing represents a definitive solution to ITAR and EAR compliance. Contradictory rulings and changing political inclination may result in divergent results. The identification of multiple plausible solutions maximizes the chance of success. Furthering this inquiry will be the subject of future work.

The final regulatory hurdle, albeit perhaps the least taxing, is to obtain NOAA approval if the satellite will be imaging the Earth (either as a mission element or incidentally). Details for how to obtain a license of this type will be included with OPEN documentation.

Reduced Mission Complexity

Mission complexity is a key driver of cost and schedule overruns as well as mission failure. Complexity obfuscates issues, preventing their detection and remediation until (particularly in the context of an orbital spacecraft) it is too late to correct them. The SQUIRM [30] model details many of these risks and discusses how these are further intensified by the involvement of students who (due to age, training level and other factors) are not as well equipped to deal with them as professional engineers would be.

OPEN dramatically reduces mission complexity by providing a known-good starting point. This is a dramatic simplifier, from a management perspective. Instead of having to track and test every aspect of the project, testing can proceed based upon the predefined testing script. Any changes to the base OpenSat design can be tracked and corresponding changes to the test plan correlated with these design changes (and suitably evaluated, etc.). By providing this starting point, a CubeSat project changes from a massive management enterprise to a more manageable one.

It has been asserted [31] that a test plan is not a complete testing solution. This is indisputable. The test plan seeks to minimize testing time and frustration by identifying what needs to be tested and how to test it. This does not preclude small quirks from turning into large problems, which must be remediated on a case-by-case basis. Adequate time and budget must be allocated for this phase. Future work will include statistical analysis of integration and testing time its associated budget consumptions (for base OPEN configuration). This work will permit the creation of a set of integration and testing best practices for use with the OPEN framework.

Catalyst for Innovation

A core tenet of the OPEN approach is to encourage innovation and to stimulate the development of new CubeSat systems and capabilities. Building an OPEN-style spacecraft encourages participants to think outside the box. It allows innovation in one particular area of expertise by providing a reliable and capable reference for other major spacecraft components. Adopters of OPEN will find that they are able to manufacture the vast majority of a capable CubeSat without needing to dedicate significant institutional resources developing in-house solutions for constituent subsystems. As CubeSat programs gain experience working with OPEN hardware they are free to focus time and resources developing payload components or specialized subsystems with new and enhanced capabilities instead of basic satellite hardware.

As a second noteworthy catalyst for innovation OPEN employs is a creative use of internal space. OPEN-style spacecraft have a large internal space reserved for payloads or experimental satellite hardware. The central cavity of the spacecraft is payload compartment 5 cm x 5 cm x 10 cm in size. The presence of such a large open space on an otherwise dense and minimalistic form-factor affords OPEN adopters great flexibility in the design of flight payloads for technical demonstrations or scientific investigation.

9. ANALYSIS & COMPARISON TO OTHER APPROACHES

A basic CubeSat configuration [31] utilizing a Pumpkin Frame and command and data handling (C&DH) unit, a ClydeSpace EPS and a Astrodev Helium radio leaves approximately 5 cm x 10 cm x 10 cm of unutilized space, on one side of the spacecraft (due to the basic stacking mechanism dictated by the modified PC/104 interconnection approach). The basic OPEN design devotes 404.5 cm^3 to the payload, with 250 cm^3 of this space at the spacecraft's x-y center of mass. As Table 2 shows, this also allows 57.2 cm^3 for batteries, significantly more than would be available in the Pumpkin / ClydeSpace / Astrodev configuration.

Table 2. Volume Budget [15]

Subsystem	Volume Allocated
Payload	
Payload Area	250 cm^3
Payload Board	154.5 cm^3
Onboard Processing	154.5 cm^3
ADCS	77.3 cm^3
Power	
Board	77.3 cm^3
Batteries	57.2 cm^3
TT&C	154.5 cm^3

An alternate solution that has been proposed [31] to the volume problem is to expand from a 1-U to a 2- or 3-U configuration. While this may alleviate the volume issue for the 1-U configuration, it obviously is not a practical solution to the needs of a larger spacecraft (e.g., one starting with a 3-U or 6-U form factor) that needs more space. The ELaNa program's provision of free-to-developer launches may remove some incentive to maximize space utilization; however, as the program is currently only soliciting for up to 6-U craft [46] and has yet to launch anything larger than a 3-U [47, 48, 49, 50], this solution is not applicable to larger size craft. Moreover the OPEN configuration is particularly well suited to the inclusion of large focal length optical systems, as the 5 cm x 5 cm x 10 cm payload area would line up between the three 1-U areas, allowing the optics to be approximately 30 cm long.

10. CONCLUSION

The OPEN project underway at the University of North Dakota is a compelling and rich proposition for dramatically increasing the number of university and amateur small spacecraft participants. Today, high costs and knowledge-gaps prevent many otherwise qualified schools in North Dakota and nationwide from benefiting from the hands on experience of building space-capable hardware. By using open source and fabrication friendly designs, we endeavor to simplify the process of beginning a University small spacecraft program. Low cost subsystems (under $5,000 in total component parts cost) utilized by OPEN are readily modifiable to match end user specifications. This shifts the burden of participation away from funding and base component development towards more meaningful payload design and mission operation.

OPEN could have a groundbreaking influence on STEM education, potentially empowering and inspiring students across the nation to design, build and fly functional space hardware. The influx of participants and new brainpower to the application and development of small spacecraft payloads will undoubtedly generate new sensors, systems and technologies across the entire space technology spectrum. OPEN also potentially creates opportunities for the nascent NanoSat launch industry to attract a steady customer base as the OPEN stakeholder base grows over time.

The OPEN project is creating a satellite architecture that will open the door for broad popular participation in civil and commercial spaceflight. OPEN begins to solve some of the most vexing problems limiting entrance into small satellite participation: cost, complexity and uncertainty. By empowering universities and amateurs with a powerful open framework for small satellite development, the nano-satellite community will attract new participants, test innovative technologies and demonstrate increasingly sophisticated science and other capabilities of the small satellite form-factor. By empowering universities and amateurs with a powerful open framework for small satellite development, OPEN is shaping the future of the small satellite paradigm and influencing the community of stakeholders.

11. FUTURE WORK

The OPEN framework is in an early stage of development. Future work will be required to quantify the specific areas of benefit and the level of benefit of using the framework across multiple use conditions in a longitudinal study.

REFERENCES

[1] F. Morring Jr, "Changing Game" Aviation Week., Vol. 174, Issue 14, Apr. 16, 2012.

[2] NASA History Office. Sputnik and the Dawn of the Space Age. [Online]. Available: http://history.nasa.gov/sputnik/expinfo.html

[3] NASA History Office. Explorer-I and Jupiter-C. [Online]. Available: http://history.nasa.gov/sputnik/expinfo.html

[4] Comstac. (2011, May). Commercial Space Transportation Forecast. FAA AST, Available: http://www.faa.gov/about/office_org/headquarters_offices/ast/media/2011%20Forecast%20Report.pdf

[5] W.A Shiroma, L.K. Martin, J.M. Akagi, J.T. Akagi, B.L Wolfe, B.A. Fewell A.T. Ohta, "CubeSats: A Bright Future for Nanosatellites", Central European Journal of Engineering, Vol. 1, Num. 1, 2011, Available: http://www.springerlink.com/content/u688lwp60v657031/

[6] M. Swartwout, "University-Class Satellites: From Marginal Utility to 'Disruptive' Research Platforms", 18th Annual AIAA/USU Conference on Small Satellites, UT, 2004

[7] M. Swartwout, "The promise of innovation from university space systems: are we meeting it?" [Online]. Available: http://www.thespacereview.com/article/1490/1

[8] R. Twiggs, B. Malphrus, "CubeSats", Space Mission Engineering: The New SMAD, Hawthorn, CA, M.P., 2011, 25, 803-821.

[9] K.Woellert, P. Ehrenfreund, A. Ricco, H. Hertzfeld. "Cutesats: Cost-effective science and technology platforms for emerging and developing nations," Space Policy Institute, The George Washington University, Washinton, DC, 2010.

[10] J. Straub, "CubeSats: A Low-Cost, Very High-Return Space Technology", AIAA Reinventing Space Conference 2012, 2012.

[11] Tyvak Nano-Satellite Systems, Price List [PDF]. Available: http://www.tyvak.com/products/Pico/TyvakPriceList_v1.05.pdf

[12] National Aeronautics and Space Administration. Definition of Technology Readiness Levels [PDF]. Available: http://esto.nasa.gov/files/trl_definitions.pdf

[13] O'Reilly, T and Battelle, J., Web Squared: Web 2.0 Five Years On [PDF]. Available: http://gossgrove.com/sites/default/files/web2009_websquared-whitepaper.pdf

[14] CalPoly SLO. CubeSat Design Specifications [PDF]. Available: http://cubesat.org/images/developers/cds_rev12.pdf

[15] J. Straub, C. Korvald, A. Nervold, A. Mohammad, N. Root, N. Long, D. Torgerson. OpenOrbiter: A Low-Cost, Educational Prototype CubeSat Mission Architecture. Machines Vol 1, No1.

[16] Goldmine Electronics. Motor Products [Online]. Available: http://www.goldmine-elec.com/motors/

[17] Sparkfun. Qik Dual Serial Motor Controller [Online]. Available: https://www.sparkfun.com/products/9106

[18] Sparkfun. Tri-Axis Gyro Breakout - L3G4200D [Online]. Available: https://www.sparkfun.com/products/10612

[19] Sparkfun. Compass Module with Tilt Compensation - HMC6343 [Online]. Available: https://www.sparkfun.com/products/8656

[20] Raspberry Pi, Raspberry Pi Order Form [Online], Available: http://www.newark.com/jsp/search/productdetail.jsp?id=43W5302&Ntt=43W5302&COM=raspi-group

[21] Gumstix Inc, Gumstix Overo COMS [Online], Available: https://www.gumstix.com/store/index.php?cPath=33

[22] J. Samson, "Update on Dependable Multiprocessor CubeSat Technology Development", IEEEAC paper #1581, Version 5, January 20, 2012.

[23] Root, N., P. Johnson, J. Straub, R. Fazel-Rezai and R. Fevig. Bus and Communications Design and Fabrication for a Near-Space Mission. Presented at the ND EPSCoR 2012 State Conference, 2012.

[24] R. Mayers, M. Olson, N. Root, J. Berk, P. Johnson, A. Mohammad, J. Straub, A. Nervold, D. Torgerson, "A Power Conserving Hardware Architecture for a High-Performance Cubsat," Submitted to AIAA SPACE 2013 Conference & Exposition, San Diago, Ca, 2013.

[25] Spectrolab Inc. private communication, Jan., 2013.

[26] CubeSat Cookbook. Batteries [Online]. Available: http://cubesatcookbook.com/directory/batteries/

[27] Noe, C., "Design and Implementation of the Communications Subsystem for the Cal Poly CP2 Cubesat Project", Computer Engineering Department California Polytechnic State University, June 11, 2004.

[28] Laptontape.com, Low Static Kapton® Tapes, RoHS Compliant [Online], Available: http://www.kaptontape.com/Low_Static_Kapton_Tapes.php

[29] National Research Council of the National Academies. Controlling Cost Growth of NASA Earth and Space Science Missions. Washington D.C.: National Academies Press, 2005.

[30] J. Straub, R. Fevig, J. Casler, O. Yadav, "Risk Analysis & Management in Student-Centered Spacecraft Development Projects", Acc. 2013 Reliability and Maintainability Symposium, 2013.

[31] M. Swartwout, private communication, Jan, 2013.

[32] Federal Communications Commission International Bureau Satellite Division. Public Notice DA 04-1724. June 16, 2004.

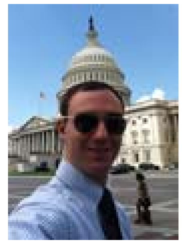
[33] J.E. Bartlett, Bartlett's Annotated ITAR [PDF]. p.21 Available: http://www.utexas.edu/research/osp/documents/annotated_itar.pdf

[34] 22 CFR (1)(M), §120.11(a)(8)

[35] M. Swartwout. "AC 2011-1151: Significance of Student-Built Spacecraft Design Programs It's Impact on Spacecraft Engineering Education Over Last Ten Year," in American Society for Engineering Education Annual Conference, Vancouver, BC, Canada, 2011.

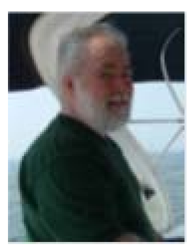
[36] Oracle Corporation. Community Development of Java Specifications [Online]. Available: http://www.jcp.org/en/home/index
[37] Linux Changes Rules [Online]. Available: http://kernelnewbies.org/LinuxChangesRules
[38] J.E. Bartlett III. Bartlett's Annotated ITAR. [Online]. Available: http://www.ndia.org/Resources/ExportImportComplianceResources/Documents/BITAR%20(1%20Sep%2012).pdf
[39] O .Diaz, "Analysis and comparison of extended and unscented Kalman filtering methods for spacecraft attitude determination", Ph. D. dissertation, Naval P.S., Monterey, CA, 2010.
[40] D.J. Barnhart, "A Low-Cost Femtosatellite to Enable Distributed Space Missions", AFIT/ENEL, Wright Patterson Air Force Base, OH, 2006.
[41] C. Mortensen, "NPS-SCAT; Communications System Design, Test, and Integration of NPS' First CubeSat", Ph. D. dissertation, Naval P.S., Monterey, CA, 2010.
[42] J. Trimble, "Space Identification in Living Color", Air Force Space Battle Lab, Schriver AFB, CO, 2000.
[43] C. Hall, "Formations of Free-Flying Gyrostat Telescopes", Air Force Office of Scientific Research, Arlington, VA, 2000.
[44] L.T. Dorn. "Nps-Scat; Electrical Power System," PhD. Dissertation, Navy Postgrad School, Monterey, CA, 2009.
[45] M. Sundahl, "Space Tourism and Export Controls: A Prayer for Relief", Journal of Air Law & Commerce, vol. 75, no. 581, 2010.
[46] National Aeronautics and Space Administration. Announcement of CubeSat Launch Initiative [PDF]. Available: http://www.nasa.gov/pdf/627968main_CSLI_Announcement_of_Opportunity_11_2_2012.pdf
[47] National Aeronautics and Space Administration. Fact Sheet for ELaNa-1 [PDF]. Available: http://www.nasa.gov/pdf/627973main_513455main_CubeSatFactsheet_Final.pdf
[48] CubeSat. (July, 2012). ELaNa 3 Launch Successful! [Online]. Available: http://cubesat.org/index.php/missions/past-launches/110-elana-3-launch-successful
[49] National Aeronautics and Space Administration. Fact Sheet for ELaNa-3 [PDF]. Available: http://www.nasa.gov/pdf/627975main_65121-2011-CA000-NPP_CubeSat_Factsheet_FINAL.pdf
[50] National Aeronautics and Space Administration. Fact Sheet for ELaNa-IV [PDF]. Available: http://www.nasa.gov/pdf/687141main_CubeSat_fact_sheet_ELaNa_VI.pdf

BIOGRAPHIES



Joshua Berk *is a Graduate Student in the University of North Dakota's Department of Space Studies. His research relates to the politics and policy of space technology development. Josh Received a BA in Politics, Philosophy and Law from the State University of New York at Binghamton, NY. He is the Deputy Program Manager of the OpenOrbiter Satellite initiative and a contributing member to the North Dakota Inflatable Lunar Habitat Project. During 2012, he worked at NASA headquarters where he had the opportunity to influence national space technology policy. Prior to commencing graduate studies, Josh was the chief student academic advocate for the 64 college campuses of the State University of New York system. At Binghamton University, Josh oversaw an annual operating budget of over $2 million, as chair of the student government. He is currently serving as the Vice President of the Dakota Space Society.*

Jeremy Straub *is a PhD student in the Department of Computer Science at the University of North Dakota. He currently serves as the Student Program Director for the North Dakota Space Robotics Program. His research is presently focused on artificial intelligence for space applications. Before returning to pursue doctoral studies, Mr. Straub held progressively responsible positions in industry. He has over 10 years professional experience in developing and managing the development of cutting-edge commercial systems, including North America's first commercial traffic-adaptive navigation system. Jeremy holds an BS in Information Technology, a BS in Business, a graduate certificate in Space Studies, an MBA and an MS in Computer Systems and Software Design. He is a member of the AIAA, IEEE, SPIE and SSPI.*



David J. Whalen *is an associate professor in the Department of Space Studies at the University of North Dakota. Prior to this, he was the vice president satellite systems consulting at IOT Systems LLC. He has been an engineer and engineering manager in the communications satellite industry for over 30 years. He has also worked on weather satellites (INSAT, GOES-NEXT), earth observing satellites (LANDSAT), and science satellites (GRO, Hubble). He is an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He has been a member of the AIAA History Technical Committee and is currently a member of the AIAA Communications Systems Technical Committee. Over the last twenty years he has written about space history and space policy in addition to his engineering work. He holds a BA in Astronomy from Boston University, an MS in Astronomy from the University of Massachusetts, an MBA from the College of William and*

Mary, and a PhD in Science, Technology, and Public Policy from George Washington University. He has taught university and industrial courses in orbit determination and maneuver planning, satellite communications, space policy, and the history of technology. His book Origins of Satellite Communications 1945-1965 was published by the Smithsonian Institution Press in 2002. He has recently finished a book about COMSAT Corporation. He has made many presentations at AIAA, PTC, CASBAA, AHA, SHFG, and NASA conferences. He has published articles and book reviews on space history, space policy, and space technology in a variety of publications including IEEE Technology and Society and Technology and Culture.

ACKNOWLEDGEMENTS

Small satellite development work at the University of North Dakota is or has been supported by the North Dakota Space Grant Consortium, North Dakota NASA EPSCoR, the University of North Dakota Faculty Research Seed Money Committee, North Dakota EPSCoR, the Department of Computer Science, the John D. Odegard School of Aerospace Sciences and the National Aeronautics and Space Administration. The participation of numerous students and faculty spanning multiple UND departments in the small satellite program is gratefully acknowledged. The corporate sponsors including GitHub Inc., who currently provide their GitHub service to the OpenOrbiter project at no charge are also greatly appreciated. Partial support for the presentation of this paper at the 2013 IEEE Aerospace Conference has been provided by the UND Intercollegiate Academic Fund, administered by the Office of the Provost.