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Increasing National Space Engineering Productivity and Educational Opportunities via Intrepreneurship, Entrepreneurship and Innovation

Jeremy Straub

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INCREASING NATIONAL SPACE ENGINEERING PRODUCTIVITY AND EDUCATIONAL OPPORTUNITIES VIA INTRPRENEURSHIP, ENTREPRENEURSHIP, AND INNOVATION

Jeremy Straub
Department of Computer Science, University of North Dakota, Grand Forks, ND, USA

Research and educational efforts related to space engineering or requiring access to space face significant startup costs. The cost of developing a 1-U (10 cm × 10 cm × 11 cm) CubeSat from scratch can be approximately $250,000. Those buying a kit must pay amortized vendor development costs on a per-mission basis, creating a lower per-mission barrier. Kit users are also constrained by being unable to make changes to vendor subsystems without incurring substantial redevelopment costs or vendor charges. The Open Prototype for Educational NanoSats (OPEN) is changing this by providing freely available design documents for a 1-U CubeSat class spacecraft and its component subsystems. The OpenOrbiter spacecraft, currently under development at the University of North Dakota, will serve to demonstrate and validate these designs. The OpenOrbiter program is also demonstrating new techniques in interdisciplinary education and how disciplines that were not traditionally included in small spacecraft development efforts can aid the program through and benefit from involvement. This article provides an overview of OPEN and OpenOrbiter as well as considering its benefits to the national aerospace engineering efforts and its educational benefits.

Key words: Small spacecraft; CubeSat; Aerospace engineering; Project-based learning; Education
OpenOrbiter spacecraft is being constructed at the University of North Dakota. OpenOrbiter is a 1-U CubeSat class nanosatellite, which will conduct remote sensing activities in low-Earth orbit. The OpenOrbiter program is also demonstrating new educational techniques. It is a large multidisciplinary project, which is providing students with the opportunity to learn how to work with students of different majors and to learn the vernacular of these related disciplines. In addition to the typical STEM disciplines involved in space engineering projects, OpenOrbiter has included students and faculty from non-STEM disciplines such as business, education, and fine arts.

This article provides an overview of the progress on and value of OPEN and OpenOrbiter. It highlights both the technical and educational accomplishments to date and places them in the context of national needs for technology development and STEM and non-STEM education.

BACKGROUND

The work discussed herein draws on several fields of prior work, an overview of which is now provided. This starts with a review of educational satellite programs. Then a brief overview of the value of small spacecraft to space-based research is presented. After this, a discussion of the changing small satellite development and operating environment is presented. Finally, the use and utility of small satellites in STEM education is presented.

A Review of Educational Satellites

In 2000, Bob Twiggs dramatically changed the concept of how small a satellite could be through the Orbiting Picosatellite Automatic Launcher (OPAL), which deployed six satellites that had similar dimensions to a hockey puck (9). The first CubeSat was deployed shortly after this, in 2003, via the Poly-PicoSatellite Orbital Deployer (P-POD) based on CubeSat specifications, which were developed by Twiggs and Jordi Puig-Suari (9). In the intervening time, further miniaturization of electronic components and other optimizations has facilitated the creation of more capable CubeSat class spacecraft and the creation of even smaller spacecraft such as Twiggs’ 5 cm × 5 cm × 5 cm PocketQub and the pocket-sized spacecraft proposed by Johnson and others (9).

Interplay has always existed between educational and research uses for small spacecraft. Thaker and Swenson have suggested that the focus, historically, has been primarily on education (24). Swartwout, on the other hand, has suggested that university programs have moved away from being predominately student engineering exercises or “beepsats” (which lack a “compelling” purpose) and can instead serve as “disruptive” platforms for research activities by taking advantage of the greater risk tolerance, student enthusiasm, and innovative ideas present in a university environment (20,22).

Space Research

Small spacecraft have been demonstrated to have significant utility in performing bona fide research activities (25). Examples of these include engineering development and testing activities such as the use of plastic printed structures (note that the conventional terrestrial 3D-printing approach creates structures, which generally contain air and may suffer from outgassing issues), deployable solar panels, advanced (including 3D-printed) propulsion technologies, and structural joints (such as Stanford’s HATTS) (2). They have also been used to collect data in support of scientific exploration. Examples of instruments carried as payloads within CubeSats include an oxygen airglow photometer, neutral hydrogen photometer, Langmuir plasma probe, electric field boom, VLF receiver, SSD spectrometer, transient photometer, Langmuir plasma probe, tether, and Nitol tether (24). Chirayath has demonstrated their utility for high-resolution imaging as part of a multi-CubeSat constellation (7).

Changing Small Satellite Environment

Woellert proffers that “only a few years ago, one would risk their credibility if they suggested the CubeSat was a viable platform for interplanetary missions”; this, however, is now being seriously researched with two respected conferences focusing on this topic (one dealing with exclusively CubeSats and one with small satellites) (26). A few years before this, the notion of performing a bona fide science
mission with a CubeSat would be questioned; now their utility for this is generally accepted.

Like many maturing fields, the costs and the barriers to entry to CubeSat construction have declined somewhat. Vendor kits make entry available to anyone with suitable funding and the capability to perform payload integration and testing (14). This stands in contrast to earlier missions for which design from the ground up was a necessity. On the spacecraft side, the initial barrier to entry has fallen considerably: from a cost of $250,000 to develop a CubeSat from scratch (and a requirement to have access to specialists in all required areas) to $40,000 plus payload hardware, integration, and testing costs (14). On the launch side, costs are also declining. Vendors have projected costs as low as $10,000 for a 1-U, 1-kg CubeSat launch into low-Earth orbit, as opposed to the $50,000 or more that some missions have paid previously (14). For educational institutions and nonprofits, a launch can potentially be obtained at no cost to the developer from the NASA ELaNa program (12). The growing acceptance and proliferation of CubeSats is also increasing the number of launch vehicles that they can obtain launch services on and the orbits for which launches are available.

OVERVIEW OF THE OPEN PROTOTYPE FOR EDUCATIONAL NANOSATS

The Open Prototype for Educational NanoSats is a part of the solution for increasing the accessibility of space by educators, students, and researchers. This section provides a technical description of the OPEN design; the next provides an overview and assessment of the benefits provided by the OPEN concept.

Mechanical Design

The structural design utilized by OPEN was inspired by a configuration described by Samson where GumStix were placed around a central cavity that was needed for another purpose (11). The OPEN design is comprised of a central 5 cm × 5 cm × 10 cm payload bay surrounded by four module slots, which are formed by the corner posts of the CubeSat. Figures 1 and 2 depict this visually (17).

By placing the modules on the exterior of the spacecraft, several benefits ensue. First, the modules have direct access to deploy parts, if required. For example, the antennas can be deployed directly from the communications board, as shown in Figure 3. Second, the modules can utilize the overhang space between the required position of the CubeSat corner posts (which are positioned based on the location of
the rails in the P-POD) and the side of the P-POD, as shown in Figure 4 [based on the specifications in (6)]. This increases the usable volume of the CubeSat by approximately 30%. Table 1 presents the volume budget of the OpenOrbiter spacecraft using this OPEN configuration. Third, by placing the payload bay in the center of the spacecraft, a propellant storage tank can be placed at the center of mass of the spacecraft. This is desirable as it prevents changes to spacecraft balance as the propellant tank is depleted. Fourth, this configuration allows the printed circuit board (PCB) of the modules to act as part of the structure, reducing the amount of mass and volume devoted to structural members. Fifth, the slotting approach (and top-cap) ensures that a board that is not seated completely is visually noticeable and that, once secured, boards cannot unseat themselves (as they are secured in place). Finally, this approach can be scaled to larger

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**Figure 1.** CAD drawing of the OPEN spacecraft form factor (4).

**Figure 2.** Diagram of space utilization in the interior of the OPEN form factor (17).
spacecraft sizes such as 2 U (20 cm × 10 cm × 10 cm) or 3 U (30 cm × 10 cm × 10 cm) and create the longest possible length for an imaging system.

**Electrical Design**

The electrical design of OPEN is designed to maximize compatibility with other spacecraft to the greatest extent possible (considering the physical design differences). The four subsystem boards are electrically, but not physically, stacked. A connector on the top and bottom plates of the spacecraft provides connectivity to the board electronically above and below the current board, respectively. PC/104-style connectors are also utilized to enhance the potential for compatibility.

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**Figure 3.** Board diagram compliant with the OPEN specification (17).

**Figure 4.** Diagram of usable space inside a P-POD deployer.
One board is devoted to the payload. For Open Orbiter, this will house a purpose-built payload processing system (comprised of four GumStix WaterSTORM computer-on-module units), which will perform image capture planning and image enhancement and mosaicking. Other OPEN-based missions can utilize this space in the way that best serves their payload. A 13 cm × 13 cm or 15.5 cm × 15.5 cm battery storage area (depending on payload support configuration) exists in each of the four corners of the spacecraft (adjacent, diagonally, to the corner posts) to facilitate the storage of four (full-height) or eight (half-height) batteries.

Software

The OPEN framework also includes software for operating the spacecraft and for controlling the spacecraft from the ground. Figure 5 depicts the software operating flow (including OpenOrbiter-specific payload elements for illustrative purposes).

The operating software is based on an operating loop where, during each iteration, items are removed from inbound queues (from the ground station, subsystem messages, and the payload processing system, if present). The task with the highest priority is selected to be performed and triggered. Once this task is done, a specified period of time elapses, or a job with an interrupting priority is received, a new job is selected, and the cycle repeats. Note that the job being performed is instantiated in a new process, thus allowing the operating software to continue to receive and respond to subsystem messages and to interrupt and remove items from queues to storage. The operating software ensures that the queues have been completely emptied before selecting a new task to instantiate to prevent a lower priority task being selected over a queued higher-priority one.

Operations

The mission operations plan for the base OPEN design is based on controller-supplied tasks, which are decomposed into component jobs by the software onboard the spacecraft. These jobs can be performed immediately or, otherwise, will be stored until the appropriate point in time (e.g., when the spacecraft is over the imaging target). The ground station software checks jobs to determine whether they conflict with other jobs that the ground station is aware of (the architecture presumes that multiple ground stations might be used and be out of synch, meaning that some jobs exist on the spacecraft that the ground station is not aware of). Once the job is transmitted to the spacecraft, it is decomposed by the payload processing software (which, in the case of OpenOrbiter, runs on the separate payload processing computer unit; on other OPEN-based spacecraft, this may run on the main flight computer), which breaks it into tasks, which are sent back to the operating software. The operating software then checks these tasks against those that are already scheduled and identifies conflicts. Any conflicts that cannot be resolved without violating job constraints (e.g., a job could be moved to another time within its acceptable performance range automatically but not to a time outside the range) are sent to the ground station operator during the next communications window for conflict resolution. Figure 5 provides a high-level overview of this process.

Projected Cost

The projected cost of the OPEN design, which excludes the mission-specific payload elements, is presented in Table 2, which is based on Berk et al. (3). The OpenOrbiter configuration adds marginally to this: $556 for four GumStix WaterSTORM COM units for the payload processing and approximately $500 to $700 for a camera (the PCB fabrication costs presume the fabrication of four PCBs—one for each module, as a module cannot be left empty, even if unused). Thus, a complete spacecraft, at least for imaging, can be built for a parts budget of around $5,000; obviously, different payload configurations may increase parts costs significantly.

### Table 1. OPEN Volume Budget

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Volume Allocated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td></td>
</tr>
<tr>
<td>Payload area</td>
<td>250 cm³</td>
</tr>
<tr>
<td>Payload board</td>
<td>154.5 cm³</td>
</tr>
<tr>
<td>Onboard processing</td>
<td>154.5 cm³</td>
</tr>
<tr>
<td>ADCS</td>
<td>77.3 cm³</td>
</tr>
<tr>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>Board</td>
<td>77.3 cm³</td>
</tr>
<tr>
<td>Batteries</td>
<td>57.2 cm³</td>
</tr>
<tr>
<td>TT&amp;C</td>
<td>154.5 cm³</td>
</tr>
</tbody>
</table>
Figure 5. Operating flow for OpenOrbiter spacecraft (17).
of value received are discussed. A value model is presented in Figure 6 and expanded upon in the following sections.

Reduced Cost Levels

The reduced cost levels made possible by OPEN stem from two sources: the freely available designs reduce the amount of design and development work that is required, and costs are reduced by design simplifications and optimizations.

Twiggs and Malphrus proffer that the design and implementation of a CubeSat-class spacecraft from scratch, and its testing may cost as much as $250,000 (25). The exact amount of budget attributed to activities that are eliminated or reduced is, of course, different for each project.

Projects that utilize the base subsystems without modifications will incur the lowest level of expense: the design, development, integration, and testing of their payload and the fabrication, integration, and testing of the base subsystems. Those that elect to make significant modifications or replace base subsystems with significantly redesigned ones will, of course, incur higher development and testing costs in these areas.

The impact of using the OPEN designs on overall cost merits significant analysis, as this may be a driving reason to use (or not use) the design for many developers. There are two key components of the cost model (labor costs and hardware costs) presented in Figure 7, which are directly influenced by the decision of using the OPEN designs.

Table 2. Labor Level Comparison

<table>
<thead>
<tr>
<th></th>
<th>OPEN</th>
<th>From Scratch</th>
<th>Vendor Kit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Integration</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Testing and validation</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Operations</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Management</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
</tbody>
</table>

The other element of the cost is the time that must be spent to assemble and test all of the components. For many projects, this may not be a direct project cost. For example, for a course-integrated project, student time may be contributed for learning purposes and faculty member time compensated via faculty teaching salary. Other projects, for example, those with research purposes, may directly incur significant labor costs. In any event, these costs are decreased by having a complete set of design documents and assembly and testing instructions for the base configuration.

QUALITATIVE EVALUATION OF THE VALUE OF THE OPEN PROTOTYPE FOR EDUCATIONAL NANOSATS

This section reviews several sources of prospective value that may be generated for users of the Open Prototype for Educational NanoSats. For each category, the source of the value is discussed, the value is quantified (to the extent possible), and factors that may contribute to the level of this type of value received are discussed. A value model is presented in Figure 6 and expanded upon in the following sections.

Figure 6. Model for assessing value of spacecraft approach.
to use an OPEN-based design, to develop from scratch or to procure a vendor kit. An additional area (laboratory equipment costs) may be impacted, depending on the developers’ current equipment holdings.

**Labor Costs**

Labor costs can be decomposed into six categories: design labor, fabrication labor, integration labor, testing and validation labor, operations labor, and management labor. Each will now be briefly considered.

**Design Labor.** Relative to the build-from-scratch approach, the use of the OPEN design will significantly reduce the need for design labor. The amount of savings enjoyed will depend on how significantly the developer modifies the OPEN design, with those making no or limited modifications enjoying greater levels of savings (compared to those making more extensive modifications). Relative to the vendor kit approach, the design labor requirements for using the OPEN design without modification of the core components should be similar. In both instances, the developer still incurs some level of design costs related to designing their payload elements (and any necessary interface hardware, etc.). OPEN may simplify this as it provides an example payload module that can be used as a guide or starting point for design. Some vendors provide payload boards or starter kits, which may provide a similar benefit.

**Integration Labor.** Compared to the design-from-scratch approach, the required level of integration labor for an OPEN-based spacecraft should be roughly equivalent. In both cases, all of the fabricated components must be assembled and their combined operation tested. The vendor kit approach should have a lower level of integration required, as most vendors pretest components to ensure that they will function when assembled. The OPEN approach may outperform the design-from-scratch approach in that the prior testing of the designs and their space qualification may reduce the number of times that boards must be refabricated or repaired. This reduces the need to reperform testing to validate the performance of the repaired or refabricated boards.

**Testing and Validation Labor.** The testing and validation labor requirements for the OPEN design should be significantly less than build-from-scratch approach and greater than the vendor kit-based approach. The build-from-scratch approach will require more testing and validation labor than the OPEN approach because of the necessity of testing hardware for which the design and implementation have not validated previously. Both the OPEN and build-from-scratch approaches will require board/subsystem implementation validation. The OPEN approach’s implementation validation should require less time because the test plan (for the base OPEN system) is supplied. This will need to be developed for the build-from-scratch approach. For the vendor kit approach, this validation is performed by the vendor prior to shipment. Because of the possibility of damage in shipment, a limited level of validation must still be performed; however, this can focus on testing processes instead of lower-level testing.
phases that are particularly management intensive (i.e., mostly performed by managers as opposed to staff). These phases include design, development, integration, testing, and mission operations. It is expected that the integration and testing phases will take longer and thus require more management time than with the vendor kit approach. Additionally, the design and development (excluding payload development) management time will be in addition to the time requirements of the vendor kit approach. It is anticipated that for virtually all missions, the vendor selection management will be significantly less than the management required for the build-from-scratch approach.

The OPEN approach requires management in all phases, like the build-from-scratch approach, and (again) no one phase is particularly management intensive. The design phase will be limited to making any modifications required to the OPEN designs and payload design. Thus, less work is required during this phase, and this, thus, means a commensurate reduction in the number of management hours that must be spent. Reductions, compared to the build-from-scratch approach, will also be enjoyed during the development/fabrication, integration, and testing/validation phases, due to the fact that the core OPEN design has already been validated, limiting the amount of design-attributable errors that must be detected and rectified. It is expected that the level of management labor required for an OPEN design will be more than what is required for a vendor kit and less than what is required for using the build-from-scratch approach.

Summary. The OPEN approach, overall, will require more labor than the vendor kit approach and less labor than the design-from-scratch approach. Table 2 presents a comparison of the level of labor required in the different areas discussed.

Hardware Costs

Hardware costs are also affected by the approach chosen. These costs can be broken into three categories: parts cost, waste and damage cost, and testing materials and supplies cost. Each will now be considered.

Parts Costs. The level of parts costs that are incurred varies significantly between the three
options. The OPEN approach and the build-from-scratch approach will have the lowest level of parts costs as both will involve buying small components and board fabrication services. The vendor kit approach will cost significantly more in this category as the parts procured (either as a single complete, excluding payload, kit or as individual subsystem components) will include amortized vendor development costs, vendor-incurred waste/risk costs, and vendor fabrication labor costs.

**Waste and Damage Costs.** Waste and damage costs are an inherent component of any development project. These costs will be particularly high for projects that must utilize parts for testing designs that may be deemed dysfunctional and thus require rework and the disposal of components that cannot be salvaged. Damage costs are increased by inexperienced developer staff that may inadvertently break parts during assembly or testing. It is expected that the develop-from-scratch approach will generate the highest level of waste and damage costs. A developer using the OPEN framework will enjoy some savings versus the develop-from-scratch approach because the designs have already been validated reducing the level of development and redevelopment required. The fabrication instructions provided should also have a positive impact as they should decrease the level of errors that occur during fabrication.

The vendor kit approach may decrease waste costs, as the need for consuming parts for testing is eliminated (except for the custom payload). Damage costs should be reduced due to the fact that most assembly is conducted by the vendor (and thus their cost, which is factored in to their pricing). However, if damage occurs during integration or testing, it could be particularly expensive as an entire assembly may need to be replaced, if damaged.

**Testing Materials and Supplies.** Materials and supplies may need to be consumed for testing purposes. The amount of cost incurred for these should be small, relative to the total cost of the spacecraft. It is likely that more testing materials and supplies will be needed for the OPEN and build-from-scratch approaches, as testing will be required at the component and assembled subsystem level in addition to the integration testing that will be required for all approaches.

**Laboratory Equipment Costs**

The impact of the approach chosen on laboratory equipment costs is more difficult to quantify as it depends on several factors. Chief among these is what laboratory equipment the developers already possess. A developer (such as a major university) that already has electrical and mechanical engineering laboratories may already possess most, if not all, of the laboratory equipment. Furthermore, any equipment that is procured may serve multiple uses and certainly could serve multiple spacecraft missions. Given this, the equipment may not be procured using mission funds, or the mission may only be required to contribute a portion of the overall expense. Owing to the wide variety of possible outcomes, this category (and launch costs, which are not directly affected by the approach selected) will be treated as neutral. The laboratory equipment costs may have an impact for a given developer (and should be considered in this context); however, their impact cannot be suitably generalized.

**Summary**

The type and cost of labor being utilized may be the driving decision factor in terms of what approach is undertaken. Those with high labor costs who do not need to modify standard subsystems may find a vendor kit to be a preferred solution, as the labor costs required to fabricate a spacecraft from parts may exceed the vendor-amortized development costs, assembly costs, and profit margin built in to the cost of a kit. Those with lower levels of labor costs (e.g., student workers, volunteers, or participants for academic credit) may find fabrication from parts to be a more prudent choice. If substantial changes are required or the base OPEN design is not suitable for the developer’s needs, then the development-from-scratch approach may be required. Table 3 presents a comparison of the level of each cost incurred for each category.

**Elimination of Recurring Amortized Vendor Development Costs**

The removal of vendor amortized costs has been discussed as part of the general topic of cost reductions, in the directly proceeding section. The value of removing them on a recurring basis bears special consideration. Swartwout proffers that a number of institutions have had difficulty initiating a second
small spacecraft program after the completion of their first. Institutions that develop a spacecraft from scratch face a significantly lower barrier to a second spacecraft, compared to those who buy a vendor kit (21). The first spacecraft incurs the design costs and significant testing costs related to identifying and rectifying design issues. Of course, the later program must still incur hardware, assembly, and testing costs; however, the overall cost is significantly less than that incurred by the first spacecraft. Even if changes need to be made (due to a changed mission or other factors), the work on the first mission reduces the costs of the subsequent ones. OPEN allows an approximation of this, starting with even the first mission, as many development costs can be avoided and testing and other costs reduced. Of course, the development of local competency and a trained staff will not occur immediately; however, the costs can be significantly lower than with a vendor kit.

For commercial reasons, the level of profit enjoyed by vendors (over marginal unit fabrication and assembly costs) is not known. It would seem, however, that this must be a significant portion of the cost of the spacecraft (or components) given the parts costs previously presented for the OPEN design and the legitimate need for the vendor to recover design expenses over a small number of units.

This benefit will be enjoyed by all OPEN users. However, those users with a greater number of missions (and particularly those with higher frequency, as this will serve to minimize retraining and other costs and increase fabrication speed and thus lower costs as staff gains experience) will enjoy greater levels of benefit.

Ease of Modification and Extensions of Design

Because all of the designs and testing plans for the OPEN framework are freely available, in addition to providing a turn-key solution, it provides an excellent starting point for developers who seek to create a CubeSat with unique capabilities. With a kit-based approach, the developer would, at a minimum, be required to redevelop (from scratch) the subsystem that they desired to alter and integrate this with other vendor-supplied spacecraft components. Alternately, they could pay the vendor to develop the new or modified component. With OPEN, the developer can start from the known-good design documents, fabrication instructions, software, and testing plans and make the changes that are required to adapt the particular piece of hardware to the developer's requirements. The level of cost savings attained will, of course, depend on the magnitude of changes required. The savings can be conceptualized through identifying the percentage of the subsystem or component that is left unchanged. Obviously, this results in little value for a component or subsystem that is being completely redesigned and significant value when a small change or addition to a subsystem is required.

Allows Focus on Area of Interest

The OPEN framework facilitates the construction of a partially modified CubeSat by developers that may seek to perform subsystem development or an engineering experiment that focuses on a single subsystem. Using OPEN allows the researcher (or student project group) to lower project cost (as opposed to buying components) and also have the flexibility to use the OPEN subsystem as a starting point (or integration reference) for the custom-developed subsystem. It also facilitates a gradual transition to a custom-developed spacecraft: OPEN components can be used and modified, as desired, or replaced with custom-designed components.

Benefits Related to Export Control (EAR/ITAR)

Both the International Trafficking in Armaments Regulations (ITAR) and the Export Administration Regulations (EAR) recognize (among others) two types of exemptions: fundamental research and public domain. The former exempts items and documentation created as part of a university research project, subject to certain limitations. The latter exempts documentation of a type that would normally be available at a library or at a conference open to all (technically qualified) individuals. The former exemption is more helpful, as it has been taken to include both the technical documentation and the actual hardware. If

<table>
<thead>
<tr>
<th></th>
<th>OPEN</th>
<th>From Scratch</th>
<th>Vendor Kit</th>
</tr>
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<tbody>
<tr>
<td>Labor costs</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Equipment costs</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Laboratory equipment costs</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
</tbody>
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compliant with the fundamental research exemption, OPEN documentation and hardware (produced at academic institutions, subject to the limitations stated in 22 CFR Chapter I, Subchapter M 120.11(a)(8) and 15 CFR §734.3 and §734.8) can be made available to non-US nationals (18). This allows foreign students to be included in small spacecraft development projects and for the OPEN materials and the spacecraft components to be used for educational purposes in classes that contain foreign nationals.

OVERVIEW OF THE OPENORBITER PROGRAM

The OpenOrbiter program is developing a 1-U CubeSat based on the OPEN designs, which will be launched into a low-Earth orbit at an altitude of approximately 300 to 350 km to conduct Earth remote sensing. This section provides an overview of the OpenOrbiter program. It starts by reviewing the program’s objectives. Then, it discusses the implementation of the program. Finally, the program’s plans and progress-to-date are discussed.

Objectives

OpenOrbiter seeks to demonstrate the capability of the University of North Dakota (UND) to develop a spacecraft, provide educational benefits to participants, collect remote-sensed data, and demonstrate the OPEN framework’s space worthiness. The primary and secondary objectives of the OpenOrbiter spacecraft are now presented (17).

Primary. To demonstrate the capability of UND and other participating institutions to design and develop a functional small spacecraft. This spacecraft shall test the technology and validate the performance of the Open Prototype for Educational NanoSats designs.

Secondary. To develop a remote sensing payload for the visible portion of the electromagnetic spectrum suitable for Earth science, planetary science, intelligence, space situational awareness, and other applications.

To demonstrate and test an innovative structural design, layout, and electrical configuration for the CubeSat form factor.

To demonstrate the capabilities of North Dakota educational institutions and program team members to design, develop, and operate a small satellite in preparation for larger missions.

To provide educational opportunities related to spacecraft design, aerospace project management, engineering, and computational sciences for students and others associated with the project.

Implementation

The OpenOrbiter program has been implemented as a student-run research group at the University of North Dakota. Students and faculty from numerous departments spanning five colleges within the university are involved. Figure 8 shows the organization chart for the OpenOrbiter program. As shown, each student-led team has a faculty mentor who provides support and guidance, as required.

The organization’s scope goes beyond just the staff required for building the spacecraft, however. Teams have been created, which are devoted to analyzing and maximizing the program’s value in the context of national and local policy objectives. Teams also exist to perform outreach and publicize the ongoing work. All teams support the overall goals (listed in the previous section) through their actions.

Plans and Progress

The OpenOrbiter program has a four-phase plan. The first phase is comprised of the design of all of the subsystems and software that are required for the spacecraft. The second phase consists of the fabrication of all of the electric and mechanical components and the development of the software. The third phase consists of integration and system level testing (unit level testing occurs during phase two to validate the correct fabrication of each component). Finally, the fourth phase consists of orbital operations. During this phase, the mission operations team will issue instructions to the spacecraft and evaluate the spacecraft’s performance. Additionally, scientific (Earth image) data will be collected during this phase.

The design work for several subsystems is complete, and, for others, it is ongoing. Future work will include the completion of the previously presented plan.
They are also able to see how project management and other techniques apply in the way that only a large project can demonstrate (as, in many cases, smaller projects forgive oversights and mistakes in these areas).

**Assessment of Value to Student Participants**

The value of the OpenOrbiter program to student participants has been assessed in five areas: improvement of technical skills, improvement of spacecraft design skills, an increase in excitement about space, improvement in presentation skills, and improvement in comfort-giving presentations (19). Positive change was shown in all five categories. Figure 9 shows the average improvement by area for all students. Figure 10 shows the improvement by students in each category, only for students that have shown improvement in this area. Both are presented in terms of a nine-point scale and are based on surveys of participants.

In addition to the skills surveyed, respondents identified several other areas of benefit. These included gaining experience related to leadership, teamwork, and communications.
Future work will include the completion and testing of the OpenOrbiter spacecraft, its validation through on-orbit operations, and the release of the OPEN documentation (updated based on the OpenOrbiter experiences). The educational benefits will be assessed over the remainder of the program’s duration. It is also desirable to perform longitudinal tracking of student outcomes beyond the end of the program.

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REFERENCES