# Initial Results of the First NSF-Funded Research Experience for Undergraduates on Small Satellite Software

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## ABSTRACT

This paper presents preliminary results from the first year of the first National Science Foundation (NSF) funded research experience for undergraduates (REU) with a focus on small satellite software. It begins with a discussion of prior work on the development of an open-hardware, open-source software CubeSat, the OpenOrbiter project and the Open Prototype for Educational NanoSats design, and how this served as foundational work for the REU. A brief discussion of the evaluation techniques used in this program is presented as are the results (which serve as a point of reference for which to compare those from the REU). Next, the REU concept is presented. Third, the results of student participation are discussed. Finally, the results from the REU are compared and contrasted with the results generated from the OpenOrbiter program's student participation experience during the academic year. The paper concludes with a discussion of future work, including future years of the REU program.

## INTRODUCTION

The Research Experience in Developing Software for Mission Critical Space Systems research experience for undergraduates (REU) has been designed to provide student participants with an opportunity to gain research experience related to the development of software for mission critical (and, in particular, space) applications. This work is being conducted in the context of developing software to operate a small spacecraft and (for demonstration and conceptualization purposes) a high altitude balloon payload. Through this, student participants are being exposed to multiple sub-fields of computer science.

Student participants are working on research questions relevant to and enabled by the OpenOrbiter Small Spacecraft Development Initiative. OpenOrbiter (and a thematically related precursor program) have been operating at UND for approximately three years. During this time, hundreds of students from multiple disciplines [1] have designed hardware and software to enable a 1-U (10 cm x 10 cm x 10 cm, 1.33 kg) spacecraft to be built with a parts cost of approximately $5,000 [2]. By reducing the required cost levels, the Open Prototype for Educational NanoSats (OPEN) aims to make it easier for faculty to incorporate small spacecraft development into STEM curriculum and researchers to use them for individual, lower-budget research endeavors. OpenOrbiter is being built based on the concurrently-developed OPEN specifications and is serving to validate the design through construction, laboratory testing and eventually on-orbit testing.

Projects conducted in the context of the REU have and will focus on five aspects of small spacecraft software: control software, payload (experiment) software, ground station software, mission planning software and software validation. Each of these projects is being conducted using existing OPEN designs and the OpenOrbiter hardware. Each project is advancing the OPEN designs and/or enabling a prospective mission based on OPEN.

## BACKGROUND

This section provides an overview of relevant background in several areas. First, prior work on the OpenOrbiter program is presented. Then, a discussion of project-based learning and its assessment is included. Finally, a discussion of prior work on the assessment of the OpenOrbiter program is provided.

### *OpenOrbiter Program*

The OpenOrbiter Small Spacecraft Development Initiative (OOSDI) was launched in 2012, subsequent to a thematically-related program. The program's goals, name and logo were all developed by participating students. OpenOrbiter has included significant numbers of both STEM and non-STEM students from across the University of North Dakota [1]. Some work has also been performed in collaboration with Northland Community and Technical College. OOSDI is working to demonstrate the efficacy of the designs [3] for the Open Prototype for Educational NanoSats via development, launch and on-orbit operations of an OPEN-based spacecraft. OPEN facilitates low-cost CubeSat development by making complete designs and software as well as fabrication and testing instructions and other materials publically available via the internet. With OPEN, a CubeSat can be developed for a parts cost (excluding payload components) of approximately $5,000 [2]. This is less than the $40,000 or more that might be required to procure a kit-based spacecraft or the $250,000 cost of developing spacecraft designs from scratch [4]. Reduced cost levels may facilitate greater penetration of spacecraft development and spacecraft-based experiments into affluent countries' educational systems and enable spacecraft development in less-affluent countries [5].

### *Project-Based Learning and Assessment*

A guided experiential approach to undergraduate research education is being taken by the REU program. Experiential learning techniques, also known as project or problem based learning (PBL), are based on providing students with a challenge to solve or problem to resolve. In the case of the REU participant projects, the challenge or problem is each student's component of the research question. The student participants will be required to identify required background and foundational information and collect it. The will need to assess the nature of their component of the research question and devise and implement a plan to answer this component question and/or to produce a product required to facilitate answering a larger question.

PBL techniques have previously been demonstrated to be effective across all stages of education ranging from primary to university levels (e.g., see [1, 6-10]). The techniques have also been favorably assessed for use in interdisciplinary and numerous discipline-specific activities. Prior work has demonstrated the techniques' effectiveness in disciplines including computer science [11, 12], computer engineering [13], electrical engineering [14, 15], mechanical engineering [16-18], aerospace engineering [19, 20], management [21] and marketing [22]). Small spacecraft development, particularly in a university environment, is inherently an exercise in interdisciplinary PBL. It has been shown, in the university context (e.g., see [1, 23]), to be effective in producing educational outcomes.

### *Prior Assessment Work Related to OOSDI*

A significant amount of work has been performed to assess the educational value of the OpenOrbiter program [24] and the benefits that it has provided its participants. Initial work focused on the level of increase in student self-identified status with regards to five metric areas. The attribution of this increase to program participation was also assessed and demonstrated. This work showed that a comparative level of overall benefit was enjoyed by both graduate and undergraduate student participants. The impact on team leads was particularly pronounced: they were shown to receive approximately double the level of benefit from participation. Students with greater levels of participation were also shown to receive greater benefit.

Student participants were asked [24, 27, 28] to characterize their pre- and post-participation (post-participation is defined, in this context as the current status at the time the assessment was undertaken, as many participants continued participation after this) status levels with regards to five key criteria: technical skill (discipline-specific skills in their area of focus), spacecraft design skills, presentation skills, excitement about space and comfort giving presentations. Undergraduate participants, as a group, reported gains in all five categories: 66.7% reported an improvement in the discipline-specific focus area skill and 66.7% also reported improvement in spacecraft design skills. For excitement about space, 58.3% reported a gain. A quarter of those responding (25.0%) reported an improvement in their presentation skills while 33.3% reported a gain in comfort giving presentations.

Undergraduate participant performance mirrored overall performance closely [24, 27] with 69.2% reporting an improvement in technical skills, 69.2% reporting improvement in spacecraft design skills, 53.9% reporting an increase in excitement about space, 23.1% reporting an increase in presentation skills and 30.8% reporting an increase in comfort giving presentations. It is clear from the foregoing that significant gains were made by participants and those gains were attributed (in the case of technical and spacecraft design skill increases) to the program.

Perhaps the most important and, in the context of REU development, most formative aspect of prior work was the demonstration of the impact of serving in a leadership role. Average aggregate improvement for team leads was significantly more that for non-lead participants in all categories. Team leads had a higher percentage of individuals showing improvement in three of the five categories, compared to non-lead participants. Team leads also more strongly attributed their improvement, in all categories, to program participation, compared with non-lead participants.

A limited level of assessment of correlation between participation duration and the level of benefits obtained was also demonstrated in this work: the percentage of participants in each category showing improvement was shown to have limited correlation with participation duration. Excluding outlying data, attribution levels were consistent across participation durations. Very limited correlation between grade-level, GPA and benefits was also shown. Other work [25] identified benefits that students sought from program participation and the level of interest in receiving particular benefits.

Work [28] also considered the comparative impact on program participation between computer science and other students. The average level of the sum of improvement (across all categories) enjoyed by computer science students was more than double (6.45 versus 3.2) non-computer science participants.

As participation time and benefit correlation is of significant interest, in regards to program planning, a follow-on study [26] assessed the correlation between participation time and level of benefit. For graduate students, a very strong correlation level was shown in the technical and spacecraft design skills categories. Strong correlation was also shown for the master's students group. This correlation was even stronger when computer science and non-computer science students were considered separately. Team leads (which included both graduate and undergraduate students) showed a moderate level of correlation between participation duration and benefit attainment in the areas of technical and spacecraft design skills and aggregate improvement.

This prior work, which serves as a foundation for the work proposed herein, is distinguished by two critical features which will also be a hallmark of the REU site. First, student participants were involved in real substantive research activities which are critical to reaching program goals. Student participants were aware of the specific importance of their area of work and when a component of the work was completed, they could identify the value of their contribution. Second, the student participants were given significant autonomy as to how the work was performed. Faculty mentors provided technical, logistical and planning assistance when needed but did not serve as micromanagers. Student participants were, thus, free to try different approaches and receive feedback (via their success or failure) on them.

## ABOUT THE REU PROGRAM

The research area, software development for mission and safety critical systems, is absolutely critical to the United States economy, national security and growth. The use of appropriate design, development and testing techniques is, of course, particularly important when a system must sustain human life or has the capability to injure humans through mal-operation. It is also important for systems that must perform in an environment (like space) where they cannot be easily serviced (or perhaps are not directly accessible at all) by humans. Thus this type of 'bullet-proof' software is needed from everything from medical devices to unmanned aerial vehicles to spacecraft. These types of projects also, in the context of education, force students to learn and utilize best-of-class design practices. This experience, thus, makes students aware of and begins to get them used to designing, programming, debugging and testing for reliability. Even if students do not end up working professionally on or researching mission critical systems, these same techniques (which students internalize through involvement in projects such as those proposed herein) can help prevent software errors which may cause mal-operation or leave the software susceptible to attack and compromise.

The particular work proposed on the Open Prototype for Educational NanoSats software is also significant because it is helping to build a framework that can be utilized by educators and researchers nationwide to facilitate their own educational or research NanoSat programs. Reducing the cost through this work will enable other institutions (such as 2- and 4- year colleges that may not have access to the internal and external funding sources of a research university) to incorporate spacecraft software design, engineering and fabrication into their curriculum. It also makes spacecraft development more accessible to faculty members (such as those whose institutions lack a legacy of spacecraft development) whose access to research funds is limited, allowing them to use spacecraft for engineering design work and to facilitate other work that requires remote sensed imagery or access to the space environment.

A key goal of the proposed REU is to move students from a dependent status, where significant mentor oversight and management is required to a more independent status where mentors can practice management by exception. This approach, whose efficacy has been demonstrated via previous efforts, is based on three key principals and four key practices.

Key Principals:

- Agency of Student Researchers – Students must be treated as individuals who are capable of and expected to accomplish research goals on their own.

- Management of Goals, Not Students – Mentors responsibilities as research supervisors relate to ensuring that research goals are completed not micromanagement of students. Students should be given autonomy in determining how work is completed unless until they demonstrate an inability to do so or unless overriding research methodology or safety concerns are present.

- Providing Information, Not Training – It is easy for faculty to fall into the role of teacher while mentoring. To maximize student autonomy, they must act as resources providing resources and assistance in identifying problem sources instead of providing tutorials on how to perform work.

Key Practices:

- Setting expectations and relevant success metrics – Mentors will be expected to set and convey expectations for performance to student participants. These expectations must be specific and assessable.

- Expecting results

- Incentivizing success and correcting failure

- Providing assistance as needed

Several classes of broader impact are produced through the proposed work. First, the research experience should be transformative for a subset of the students. It will peak their interest in discovery and point them towards a path of scientific exploration. The impact of the 30 participants (10 per year for 3 years), whose career paths may be altered through participation, cannot be overstated. These individuals may make discoveries in sub-fields of computer science or other STEM disciplines that do not even exist today. These discoveries may profoundly impact humanity.

In the nearer future, other broad impacts may ensue from these activities. The work proposed herein seeks to develop and evaluate a rotation-based approach to the research experience. During the experience, each member of the cohort will gain experience working in several different sub-fields of computer science, while contributing to the larger project common to all cohort members. All of the individuals will also gain experience in systems engineering (a component that is often omitted from undergraduate computer science degree programs). The work conducted may, thus, validate this rotational approach to undergraduate training through research emersion. It will also provide data about the specific activities conducted and their efficacy. All of this data will be broadly distributed through publication in relevant journals and conference presentations.

The proposed work will also serve to attract students to or retain students in computer science and other STEM disciplines. Computer science has been identified as an area of national need and many related STEM disciplines also lack sufficient numbers of graduates. The proposed work should also have the effect of attracting some participants to research careers in computer science or other STEM disciplines and/or teaching them how to use research methods to solve problems that they may encounter in their careers (even if they do not pursue a purely research position).

The students that participate in this program should gain an awareness of the special requirements related to developing software for a mission critical system. This lesson is emphasized via the mid-REU period visit to a North Dakota missile silo which will feature a discussion, lead by Co-I David Whalen, about the consequences of a software failure in this type of system. Work on project software development will utilize best practices for mission critical systems, facilitating student learning and internalization of these approaches. The immersion experience at the Jet Propulsion Laboratory should also reinforce this concept.

Finally, the larger project that the REU participants will be working on, the Open Prototype for Educational NanoSats, is poised to have a broad impact on STEM education. The designs, software, fabrication instructions and other documentation will enable low-cost incorporation of highly emotive space projects as part of formal and informal learning by students nationwide. OPEN will also support space engineering and space software development efforts and research efforts requiring access to space (e.g., for conducting experiments in the microgravity environment or remote sensing, etc.) by providing a low-cost template for spacecraft construction and testing.

## STUDENT PARTICIPANTS

Student participants were solicited via an open application process. Program participation was open to U.S. citizens and permanent residents (and a limited group of others with very special circumstances), in line with NSF REU program guidelines. Significantly more applications were received than slots were available and the number of program participants, for the first year, was extended by two, based on the number and caliber of applications received. Applications came from across the United States and 12 students were selected, who attend the following colleges and universities:

- Anoka Ramsey Community College
- Century College
- Gardner-Webb University
- Harvard College
- Liberty University
- Marshall University
- Oklahoma State
- University of Illinois at Urbana-Champaign
- University of Minnesota
- University of North Carolina at Chapel Hill
- University of the Pacific

Note that if a student is transferring from one institution to another at the time of program participation (i.e., they completed the spring semester at one institution and are accepted and plan to enroll in the fall at another), both institutions are listed. This is applicable in a single case.

The participants included five sophomores (who had completed their freshman year prior to the commencement of the REU), five juniors and one senior. Six of these individuals had majors in computer science. Two had majors in computer engineering. Four had majors in math and one each had a majors in biological and mechanical engineering. Some students had double majors (and thus were counted twice in the foregoing). In addition to their paid REU participation, one student planned to receive academic credit for participation in the context of a course project and three planned to receive academic credit for an independent study course.

## STUDENT EXPECTATIONS

At the commencement of their research activities, students completed a survey indicating what their expectations were for the research experience. This survey has been previously used and presented in [25].

As part of this survey, students were asked what they hoped to gain from their participation. Twenty-six possible responses were provided, which they could select from. Additionally, a blank was provided where students could indicate other prospective areas of desired benefit. One student responded indicating that an additional (not listed) benefit desired was gaining experience at another university. For the eleven respondents, the counts of those interested in each topic are presented in Table 1.

**Table 1.** Benefits expected and the number of participants expecting it.

| Benefit | # Expect. |
|---|---|
| Know. abt. spacecraft design | 8 |
| Know. abt. structured design processes | 8 |
| Know. abt. a particular technical topic | 7 |
| Know. abt. project management | 5 |
| Know. abt. time management | 2 |
| Leadership experience | 3 |
| Imp. technical skills | 9 |
| Imp. time management skills | 4 |
| Exp. working with those from oth. disc. | 7 |
| Real-world project experience | 10 |
| Item for resume | 10 |
| Imp. presentation skills | 5 |
| Inclusion as author on technical paper | 6 |
| Exp. working on large group project | 8 |
| Exp. with a structured design process | 8 |
| Exp. related to a particular tech. topic | 4 |
| Project management experience | 6 |
| Time management experience | 4 |
| Imp. leadership skills | 5 |
| Imp. project management skills | 5 |
| Under. How my discipline relates to oth. | 5 |
| Learn oth. discipline's tech. details/term. | 4 |
| Imp. chance of being hired in des. Field | 8 |
| Increased self-confidence | 6 |
| Ability to present at professional conf. | 7 |
| Recognition in the university community | 5 |

From the forgoing, it is clear that participants had significant expectations regarding their participation and that these expectations spanned numerous categories. However, the foregoing doesn't provide any insight as to what areas are most highly valued by student participants. To this end, students were also asked to rank their top three areas of desired benefit. Excluding the one write-in area (which was also indicated as a top desired area of benefit by the participant), these areas are presented in Table 2.

**Table 2.** Benefits listed as most important.

| Benefit | 1st | 2nd | 3rd |
|---|---|---|---|
| Real-world project experience | 3 | 5 | 1 |
| Know. abt. spacecraft design | 2 | 0 | 1 |
| Know. abt. a particular technical topic | 2 | 0 | 0 |
| Learn oth. disc. tech. details/term. | 1 | 0 | 0 |
| Imp. technical skills | 1 | 2 | 0 |
| Exp. working on large group project | 1 | 1 | 1 |
| Increased self-confidence | 1 | 0 | 1 |
| Ability to present at professional conf. | 0 | 1 | 1 |
| Exp. working with those frm. oth. disc. | 0 | 2 | 0 |
| Exp. related to a particular tech. topic | 0 | 0 | 1 |

| | | | |
|---|---|---|---|
| Item for resume | 0 | 0 | 3 |
| Know. abt. structured design processes | 0 | 0 | 1 |

Participants were also asked to indicate whether they are interested in seeking employment in the field related to their participation. A Likert-like scale (ranging from 9-strongly agree to 5-neutral to 1-strongly disagree) was used for responses to this question. The average of the responses was 6.64. Participants were also asked to indicate whether they believed participation would aid them in gaining employment. The same Likert-like scale for responses was used. The average of the responses to this question was 7.64. The distribution of responses to both questions is shown in Table 3.

**Table 3.** Distribution of responses to whether students are seeking employment in a field related to their participation and believe that participation will aid them in securing employment.

| Response | Seeking Employment | Aid Gaining Employment |
|---|---|---|
| 9 – Strongly Agree | 1 | 3 |
| 8 | 1 | 4 |
| 7 – Agree | 3 | 2 |
| 6 | 2 | 1 |
| 5 – Neutral | 3 | 1 |
| 4 | 2 | 0 |
| 3 – Disagree | 0 | 0 |
| 2 | 0 | 0 |
| 1 – Strongly Disagree | 0 | 0 |

Students were also asked what interested them in this project. Strong response was received to three of the prospective answers, while the other three received no response. Again, the opportunity was provided to indicate other responses. Table 4 presents the responses.

| Reason | # Indicating |
|---|---|
| Participation in particular technical area | 9 |
| Satisfaction of course requirement | 0 |
| Excitement about space / launching spacecraft | 10 |
| Benefit to resume | 9 |
| Friends are participating | 0 |
| Particular faculty member is participating | 0 |

Other reasons that were written in include working in a group on a real-world project and getting to participate in computer science related research.

## RESEARCH TOPICS SELECTED

REU participants selected topics in a wide range of areas. Each will now be briefly discussed.

### *Source Verification & Validation*

One individual pursued work to determine whether a data transmission or command originated from the purported source and whether it had been modified or not. This work is based on the presumption that capabilities beyond amateur licensing (e.g., under an FCC experimental license) will be used.

### *Convolutional Neural Networks for Pattern Recognition*

Two participants worked with neural networks for pattern recognition. One is working with convolutional neural networks to assess their capability to detect particular types of objects and animals in satellite imagery. A second is working to enhance neural network technology to enhance speed, accuracy and/or reliability.

### *Intelligent Attitude Determination and Control*

One participant is working to implement and enhance a design for an attitude determination and control system (ADCS) based on artificial (computational) intelligence principles. This system will learn and refine the spacecraft movement model based on a training regime and mission activities.

### *Data Confidentiality*

One individual is working on maintaining the confidentiality of collected image data. A technique based on image pixel shuffling is being assessed.

### *Super-Resolution*

One participant is evaluating the impact of compression on the results obtained from super-resolution algorithms. The goal is to determine the trade-offs as compression is required to move significant amounts of image data from a small spacecraft in orbit to the Earth.

### *Compression / Decompression*

One individual is working on a compression and decompression algorithm to enable the transfer of image data to/from orbit. This work, in conjunction with the aforementioned super-resolution work, focuses on ensuring that the compressed and subsequently decompressed data is still useful for various image processing applications.

### *Image Processing-Based Distance Determination*

This work focuses on determining object range from a set of cameras that could be placed onboard a CubeSat or cluster of CubeSats. A correlation approach is being utilized and enhanced for this purpose.

### *Model-Based Software Engineering*

Two participants are working on extending model-based software engineering (MBSE) techniques and applying them to the challenge of architecting and validating a CubeSat software system. One individual is working on defining functional requirements, while the other is working on defining quality requirements.

## SUMMARY AND FUTURE WORK

This paper has provided an overview of the initial results of the first NSF-funded research experience for undergraduates program with a focus on small spacecraft software development. It has provided an overview of the OOSDI program, in the context of which this REU is being conducted, and also provided an overview of prior work on the program and on PBL, in general.

An overview of the expectations of program participants has been provided and a summary of the research topics selected by participants during the first year has been presented. This program is ongoing and significant additional assessment is planned. This will include the use of the metrics discussed previously to assess comparative levels of skill prior to and after program participation as well as the use of the Undergraduate Research Student Self-Assessment (URSSA) instrument.

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