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Electrical and Computer Engineering Course

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The CubeSat Mini Project: Experiences with an Introductory Freshman Electrical and Computer Engineering Course

I. Introduction

CubeSats are a type of nanosatellites that have become very popular in recent years in educational settings [1]. They are small (10 cm on each side), lightweight (less than 1.3 kg), and use many off-the-shelf parts to keep the cost of building as low as possible (as little as $20,000 USD for a space-ready flight unit) Combined with dramatically lower launch costs, their popularity in graduate, undergraduate, and even high school and elementary settings is on the rise.

One of the authors is a ham radio operator and has a volunteer position at AMSAT, the Radio Amateur Satellite Corporation, a not-for-profit that builds and launches amateur radio satellites [2]. AMSAT, which has recently launched several CubeSats, is currently celebrating its 50th anniversary of launching amateur radio satellites. Through this work, he became involved in a project to design and build a CubeSat Simulator – a functional educational model of a satellite designed to teach the basics of satellites and space communication.

The CubeSat Simulator Mini Project was designed around the AMSAT CubeSat Simulator. The AMSAT CubeSat Simulator was designed based on an earlier model, known as the ARRL ETP CubeSat Simulator, designed and built by Mark Spencer, WA8SME, in 2009 [3]. The new Simulator has a software focus and is designed to be extensible and flexible for classroom demonstrations and activities. The CubeSat Simulator simulates rotation in space by rotating on a turntable in front of a halogen lamp, as shown in Figure 1.

Fig. 1. AMSAT CubeSat Simulator on a rotating turntable in front of a halogen lamp to simulate rotation on orbit.

The AMSAT CubeSat Simulator features a Raspberry Pi Zero W-based multi-board stack and a 3D-printed frame structure. It was designed to be low cost (less than $400 USD in components per Simulator, significantly less than the $20,000 USD for a spaceflight-ready CubeSat) and use off-the-shelf parts. It is fully open sourced, with all software and plans available on GitHub [4].

The development has been sponsored by AMSAT as part of its educational outreach mission, and the development is ongoing.

II. Villanova University ECE Freshman Projects course philosophy

ECE-1205 ECE Freshman Projects is one of the first electrical and computer engineering courses taken by freshmen at Villanova University.

For the 2009-2010 academic year, the College of Engineering revamped their course offerings [5]. In the previous years, all engineers took two courses, EGR-1700 and EGR-1705 which were an introduction to engineering design (with AutoCAD), and C programming class respectively. Each year, engineers who transferred out of the college were sent questionnaires to discover their reasons for leaving. Many of the students who transferred out after freshman year were not interested in these engineering classes, didn’t feel like they knew what engineering careers involved, and/or were turned off by material they felt they wouldn’t need (such as AutoCAD for EE majors). In order to improve retention and the quality of the education, the college created two new courses, EGR-1200 and EGR-1205 which would each consist of two 7-week half-semesters which together made up one course. The first 7 weeks kept the engineering design process of the old EGR-1700 course, culminating in a presentation on new or improved products that interdisciplinary teams came up with. For the second half of EGR-1200 and the first half of EGR-1205, the freshmen engineers would choose one out of 7 or 8 different multidisciplinary electives such as Electric Cars, Smartbeam design, Biofuels etc. This list would change every year, with one or two electives rotating out for new ones. The final seven weeks of EGR-1205 involved the students taking a course in their home department area that was designed to be engaging, and highlight areas in their chosen field, but not be overly technical in case a student wanted to switch majors after their freshman year. For the electrical and computer engineers, it was felt that an introduction to ECE topics such as sound and image processing using Matlab would meet these goals.

These changes did increase the retention rate of engineers in the college, but students felt that the last 7 weeks of the course didn’t help get them ready for courses that came later and tended to be “busy work”. Faculty also felt that this time was wasted, since following courses weren’t allowed to build on the freshman year in case of transfers, and the students only saw a few small canned projects in the electrical and computer engineering field. As a result, the College of Engineering refined the freshman year structure again starting with the 2018-2019 freshman cohort. EGR-1200 would remain the same but EGR-1205 would be replaced with a course that each department would offer their students. The goal was to keep the class hands on and entertaining, but also add major-specific technical work. While departments are free to now introduce topics which could be required for later classes, it was hoped that the courses could still be general enough to allow for students to transfer to other departments after freshman year. The ECE department created their course, ECE-1205 which would introduce the students to Matlab as had been done previously in the 7 week section of the old EGR 1205, but also introduce a new design area specifically geared for ECE students, in which CubeSats were chosen for the first year.

Approximately 75 freshmen electrical and computer engineering students at Villanova University in the Spring 2019 Semester worked on the project. This paper is focused on the CubeSat Mini Project and the results.

III. Mini project overview

The mini project was designed with the goal of allowing students to learn about CubeSats and satellite technology and understanding the role of radio and telemetry in satellite operation. The students also gain experience working in small teams on different aspects of the project, incorporating their part into the whole, giving a presentation, writing a short report, and sharing information using a Wiki.

The project was structured as the last six weeks of the semester, after the Matlab section and lessons on soldering. Each class built two CubeSat Simulators. In addition, each class brainstormed and built a new payload sensor to add to the Simulator.

The assessment was team-based, primarily on the completion of a number of building tasks. In addition, there was a Satellite Hot Topic presentation and writeup, and a final presentation and report on the build due on the last day of class.

Funding for the class was jointly provided by Villanova University and AMSAT and involved about $3000 USD in total parts. Three of the simulators built were given to AMSAT and are now being loaned to schools and shown at events. The other three are at the University and are being used for further development of the Simulator and for Senior Design Projects.

Also, a number of tape measure Yagi-Uda antennas built in the class have been used for satellite outreach activities at maker fairs, STEM and robotics events.

IV. Mini project activities

The project, along with the entire course, was run as a “flipped course”. Course videos and links were posted a few days prior to each class and students were reminded via email to watch them prior to class. The first few minutes of each class was spent answering any questions or comments on the videos. The rest of each class period was spent on an activity or on a build session. The videos created included:

- What is a CubeSat?
- Introduction to CubeSat Activity
- What is a CubeSat Simulator?
- Introduction to the Mini Project
- Antennas and Software Defined Radio (SDR)
- SDR# Application Setup
- Satellite Tracking
- Hardware Subsystem Intro Video
- Ground Station Intro Video

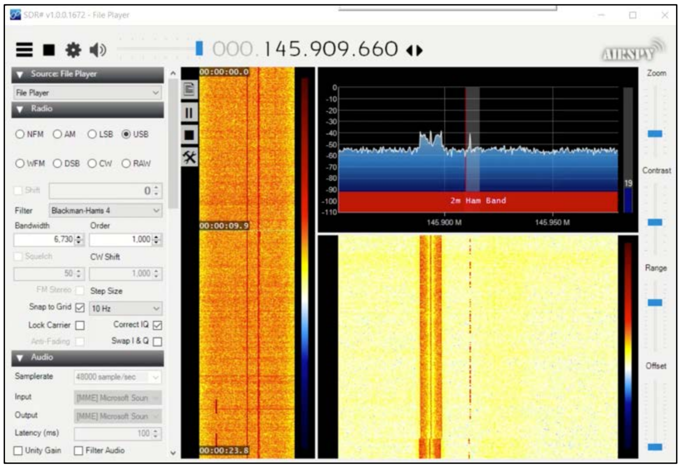
After getting an introduction to the various subsystems, students had the opportunity to specify a preference for the subsystem group they wished to work on. Nearly half the class expressed a preference, and in every case except two, their first preference was accepted. The rest of the students were randomly assigned to subsystems. Two CubeSat Simulators were built in each class, so each class had two teams assigned to each subsystem. Each subsystem had three or four students working on it.

There were several activities in the mini project. First, an introductory exercise involved online research of a CubeSat mission and a satellite launch. This exposed the students to the online databases of CubeSats and rocket launches and introduced them to wide range of mission types and objectives.

Second, another introductory activity involved building a hand-held antenna out of a metal tape measure and wood and using it to receive signals from satellites on orbit. The students worked in pairs during one class period to build a tape measure Yagi-Uda antenna, a simple hand-held antenna that cost about $10 in parts to build, based on a design by plans by Dave, KG0ZZ [6]. The parts on a “mobile antenna building cart” and some of the finished antennas are shown in this figure.

Fig. 2. Parts and completed antennas.

Students were given a link to online instructions but had to make changes to the design due to substituting tape measure tape for the coat hanger wire in the design plans. In the next class period, we went outside and tracked three satellites as they passed over campus using laptops with SDR dongles as radios ($20 per station with free SDR# software). The amateur radio satellites available were determined by the class period, but we were lucky for all classes to have at least one strong satellite pass over, built by the Chinese Amateur Satellite Group (CAMSAT). The satellite, CAS-4B, has a strong Morse Code (CW) telemetry beacon on 145.910 MHz in the amateur radio 2-meter band. Every group received this signal and heard the Doppler shift in the tone as it flew overhead. The early spring weather also cooperated for an enjoyable activity. We recorded the received data and made a short video which we shared with the class, shown in Figure 3.



Source: File Player
File Player
Radio
○ NFM ○ AM ○ LSB ● USB
○ WFM ○ DSB ○ CW ○ RAW
☐ Shift 0
Filter Blackman-Harris 4
Bandwidth 6,730
Order 1,000
☐ Squelch 50
CW Shift 1,000
FM Stereo ☐
Step Size 10 Hz
Snap to Grid ☑
Lock Carrier ☐
Correct IQ ☑
Anti-Fading ☐
Swap I & Q ☐
Samplerate 48000 sample/sec
Input [MME] Microsoft Soun
Output [MME] Microsoft Soun
Latency (ms) 100
☐ Unity Gain ☐ Filter Audio

Fig. 3. Receiving a Morse code signal from a satellite using a student-built antenna and a freeware Software Defined Radio (SDR) application on a laptop.

Third, there was one additional introductory activity called Space Hot Topics. It was a team building exercise for the newly formed subsystem teams that was also designed to cover a number of course outcomes. In a single class period, students picked a space-related controversial topic, researched it, identified an opportunity related to it, brainstormed a solution, then presented it to the class. Here is a topic list that was used:

- Environmental impact of rocket launches
- Responsibility for space junk
- Surveillance using satellite clouds – the end of privacy?
- Fair allocation of geostationary orbital slots
- Spending money on space exploration when poverty exists on earth
- Publishing orbital data on unknown satellites – does this compromise national security?
- Should we weaponize space?
- Can we justify human exploration of space vs robotics?
- Safety risk of satellites falling to earth
- Contamination of other worlds by probes and satellites
- Issues with commercialization and mining in space

As an exercise in CubeSat payloads, there was an activity where students researched various payload sensors that are used on CubeSats and chose one to add to the CubeSat Simulator. Here is the list of possible sensors that was discussed and voted on in class:

- Gyro and accelerometer - Know the position of the CubeSat in space
- Magnetometer - Investigate interaction with earth's magnetic field
- Camera - Visible or IR images
- Laser Distance Sensor - Used for CubeSat constellations
- Spectral Sensor - Analyze incident light
- UV Sensor - Detect Ultraviolet light
- Horizon Sensor – Used to detect earth horizon for positioning or photography
- GPS – Latitude, longitude, elevation
- Pressure, altitude, temperature – The CubeSat Simulator could be adapted to work on a balloon launch

- Other Sensors – A sensor not on this list can be chosen. Here are some high-level requirements for a selecting a sensor:
  - Useful for a satellite mission or high-altitude balloon mission
  - Easy to interface with an Arduino, preferably with an online tutorial and sample code
  - Inexpensive – cheaper sensors preferred over more expensive. Less than $30 is a nominal target

In the brainstorming activity, every group ended up choosing a camera as one of their top sensor ideas. However, we decided not to pursue this option as the camera on a Raspberry Pi interfaces directly with the processor, not through an Arduino interface, so it was not a good architectural fit. Instead, one class chose a laser Time of Flight (TOF) distance sensor, and two classes chose a GPS receiver.

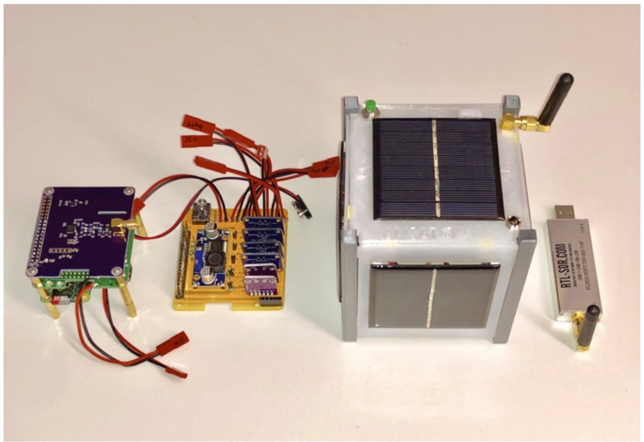


Fig. 4. An AMSAT CubeSat Simulator showing the four major subsystems: Software, Hardware, Spaceframe, and Ground Station. Not shown is Payload.

As the main activity in the project, the students broke up into small teams of 3-5 students who were responsible for building one subsystem of the CubeSat Simulator. The five subsystems are listed below, and their parts kits are shown in Figure 6:

1. Spaceframe. This subsystem involves 3D printing the frame of the CubeSat Simulator, mounting the solar panels, antenna, and switches. Also, designing and implementing the payload sensor mounting.

2. Hardware. This subsystem involves soldering the components into custom solar power board, soldering switches and connectors, and also testing and calibration of the hardware.

3. Software. This subsystem involves configuring a Raspberry Pi Zero W processor, installing and compiling software, downloading libraries, and configuring the payload interface. Also, remotely connecting and logging into the Simulator using SSH.

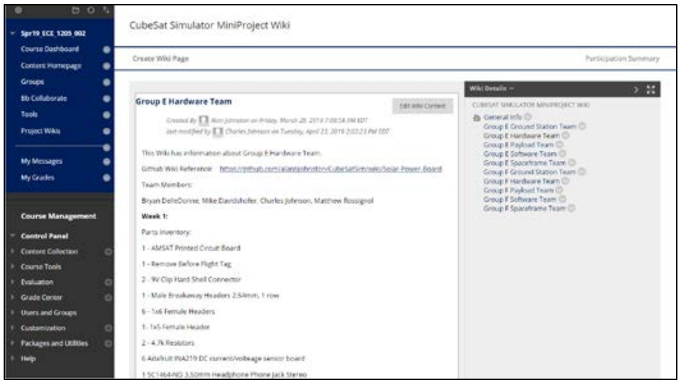
4. Payload. This subsystem involves designing the chosen payload sensor and interfacing to an Arduino and integrating the Arduino with the Raspberry Pi CPU.

5. Ground Station. This subsystem involves setting up a Software Defined Radio (SDR) ground station on a Windows laptop.

The main tool for communication between the groups and the instructor outside of class time, was course Wiki pages [7]. The instructors created a Wiki page for the Mini Project using the Blackboard Learning Management System (LMS) [8]. Sub Wiki pages were created and assigned to each group. The pages had links and information on the subsystem task. For example, in the first week, each group were given a set of tasks for their subsystem in random order. They had to put them in the right order and post them on their Wiki page along with a tentative schedule. For example, here is the task list for the Software Subsystem:

- Install Simulator software on Board Stack
- Test software interface with Arduino payload and new sensor
- Build Three Board Stack of Raspberry Pi Zero W, MoPower UPS V2, and Digital Transceiver boards.
- Install PuTTY software on laptop and use it to log into Pi without needing monitor, keyboard, and mouse
- Test basic functionality of Simulator
- Plug Raspberry Pi into a monitor, keyboard, and mouse and do initial configuration

The instructors provided comments on the Wiki as feedback. Also, additional information was posted each week on the Wiki by the instructor, and students were advised to start each class by reviewing the Wiki for changes and comments. An example Wiki page is shown in Figure 5.



Group E Hardware Team

Created By Alan Johnston on Friday, March 29, 2019 7:08:58 PM EDT
last modified by Charles Johnson on Tuesday, April 23, 2019 2:02:23 PM EDT

This Wiki has information about Group E Hardware Team.

Github Wiki Reference: https://github.com/alanbjohnston/CubeSatSim/wiki/Solar-Power-Board

Team Members:

Bryan DelleDonne, Mike Davidshofer, Charles Johnson, Matthew Rossignol

Week 1:

Parts inventory:

1 - AMSAT Printed Circuit Board

1 - Remove Before Flight Tag

2 - 9V Clip Hard Shell Connector

1 - Male Breakaway Headers 2.54mm, 1 row

6 - 1x6 Female Headers

1- 1x5 Female Header

2 - 4.7k Resistors

6 Adafruit INA219 DC current/voltage sensor board

1 SC1464-ND 3.50mm Headphone Phone Jack Stereo

Fig. 5. Subsystem Wiki Pages

Also, in the first week, teams were given a kit of parts and had to inventory and identify all the parts. The kits are shown in this figure.

Fig. 6. Subsystem Parts Kits.

The instructions used for each subsection were provided on a GitHub Wiki page. Feedback and corrections on the instructions were used to improve the documentation.

During the last 10 minutes of the final class period each week, students were reminded to write up a short summary of the accomplishments and activities of the week. This provided a running progress report.

In the final weeks, the teams had to work together to integrate the subsystems.

V. Results of the project

All groups successfully completed their CubeSat Simulator builds.

A CubeSat Simulator telemetry signal received on a Ground Station is shown in Figure 7, while data from the Hardware group is seen in Figure 8.

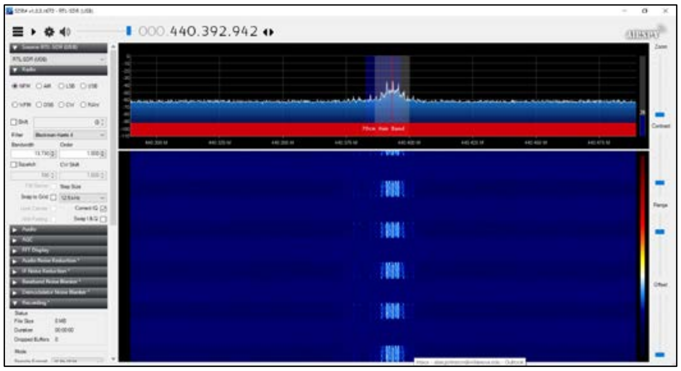


Fig. 7. CubeSat Simulator Telemetry Signal Received on a PC Ground Station.

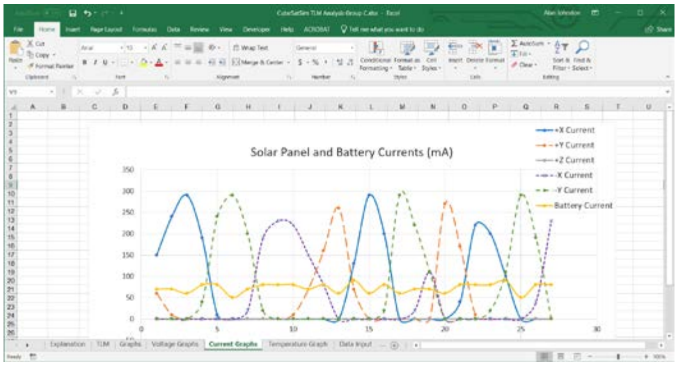


Fig. 8. Solar Panel Current Telemetry Decoded and Plotted on a Spreadsheet.

The variable aspect of the payload sensors introduced the students to real-world design issues. These sensors were low cost (about $15 each) and were easily acquired but were not tested out beforehand since it was unknown which sensor a class would choose. Therefore, there was no guarantee of successfully integrating the sensors into the CubeSat. This variability worked well, teaching the students lessons on planning, testing and debugging and resulted in successful final products. It was discovered that the Time of Flight laser sensor worked well with minimal issues, while the GPS sensor was a little touchy, and required placement very near a window to receive a signal.

The integration with the CubeSat Simulator turned out to be a little more difficult than planned, but all groups managed to succeed in getting at least one piece of sensor data incorporated in their telemetry. This part of the project will require more development in the future.

We had 5.5 hours of in-class build time scheduled. We also scheduled one additional optional session of 1.5 hours. All groups completed their build activities in this time. This allowed us to estimate the total build time of about 20 hours for the CubeSat Simulator. Two student-built CubeSat Simulators are shown in Figure 9.

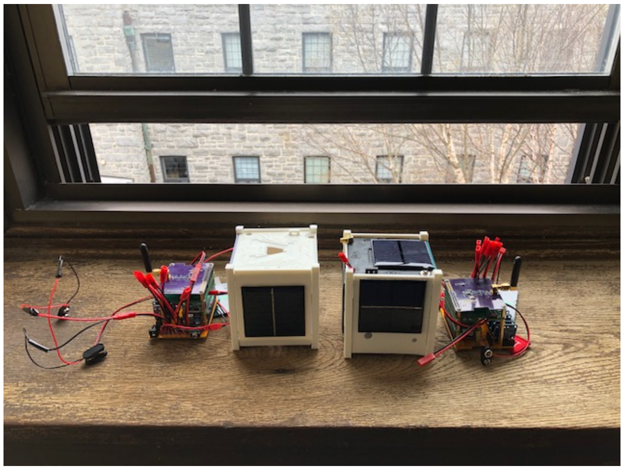


Fig. 9. Student-Built CubeSat Simulators.

VI. Lessons learned

We learned by doing this mini project that the students enjoyed the challenge and learned a lot. Many students were left wanting to know more about how the Simulators worked and how actual CubeSats are designed. In in this introductory mini project we don't have time to get into this detail, but leaving the students wanting to know more seems like a good outcome. While it is too soon to determine if this will increase ECE retention rates, the student survey response indicates the students enjoyed the class and the challenge of having to solve open ended problems.

One area where we received a lot of feedback was in the area of inter-team communication. Due to the division of work, towards the end of the project, the teams had to communicate and work together to integrate their subsystem into the Simulator. Many students commented how difficult this was, and how they wished they had done a better job.

Some of the teams also finished their part early or had to wait on another team to test and integrate their subsystem. There were also comments that the directions lacked detail and clarity.

VII. Future ideas

In the future, we plan to make some small changes to the project. The design of the actual Simulator boards has changed which should simplify and reduce the build time. We also plan to add one more week to the project. The additional time will be spent on two activities. One class period will be spent with students connecting to a web-based SDR, OpenWebRX [9] which allows students to tune in and listen to signals using just a web browser on their laptop or phone. We now have a Lindenblad satellite antenna [10] mounted on the roof of our building, so we will connect over the internet to this antenna which should provide some interesting signals, both on orbit and terrestrial to listen to. The other activity will be spent on students decoding and interpreting telemetry signals from the student-built Simulators in the classroom. We will start with interpreting basic nominal telemetry, then we will simulate various types of failures, and the students will use the received telemetry to diagnose the failure.

We also plan to discuss inter-team communication and provide some guidance on this to the teams. Perhaps we could devise an activity early in the project that forces the teams to communicate, and then use that experience to discuss the issue and how to do better.

Having some additional optional tasks ready for the teams that finish early or are waiting on another team would be another improvement.

Another idea is to have a cross training session, where one team trains another team about their subsystem, how it works, how to use it, and the function that it fulfills in the project.

VIII. Conclusions

In conclusion, we believe that the CubeSat Mini Project was an effective project for freshmen electrical and computer engineering students. Students enjoyed the challenge of an open-ended hands-on problem, were successful in working in teams to create a finished project and learned some fundamentals of communication and signals.

IX. References

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