University of Hawaii's Spaceflight-Ready, Low-Cost, Open-Source, Educational Artemis CubeSat Kit

1680 East-West Road, POST 501, Honolulu, HI; 310-710-8220
aksel@hawaii.edu

ABSTRACT
The Artemis CubeSat Kit is a spaceflight-ready, low-cost, educational 1U CubeSat kit, which acts as a foundation enabler in aerospace engineering education and commercializing small satellites. The hardware kit accompanies a standalone “Spacecraft Mission Design” curriculum in the public domain, which includes a self-guided course outline, textbook, and digital lab modules. Funded by NASA’s Artemis Student Challenge Program, the Kit is developed and maintained by students attending the University of Hawaii at Manoa and supervised by the Hawaii Space Flight Laboratory (HSFIL). The purpose of the Artemis CubeSat Kit and accompanying curriculum is to provide educational accessibility for university-level students and faculty interested in designing, building, and flying their own small satellite missions. This paper describes the technical design of the Artemis 1U CubeSat, the topology of the standalone curriculum, and the lessons learned by the team while developing the Artemis CubeSat Kit.

INTRODUCTION
According to the most recent 2021 Accreditation Board for Engineering and Technology (ABET) evaluation, only 77 universities in the United States have ABET-accredited aerospace or aeronautics undergraduate programs (ABET, 2021). This suggests that of the 689 ABET-accredited universities in the United States, approximately only 11% of ABET schools have aerospace programs. More than half of the states, 23 out of 50, do not have an aerospace program.

As technology has advanced, the complexity of building a spacecraft has steadily decreased. What would typically be achieved by engineers with Ph.D. and Master’s degrees can now be achieved by undergraduates. Even students below the university level are able to get involved in aerospace, such as the middle and high school students who developed and successfully deployed small research satellites in 2018 (Jackson, 2018). However, the number of aerospace accredited schools do not reflect the lowered educational barrier to aerospace technologies.

The Artemis CubeSat Kit is a 1U low-cost, spaceflight ready educational cube satellite and a collection of educational materials. The educational materials accompanying the Artemis CubeSat Kit cover all spacecraft bus subsystems in theory and engineering implementation. The online course (part of the educational materials) is intended to be comprehensive of (LEO) missions and take students from missions design to flight. Both the designs for CubeSat and educational materials are in the public domain.
The Artemis CubeSat Kit is funded by NASA's Artemis Student Challenge Program, whose interest is to allow students to develop innovative technologies for space exploration (Brown, 2020). Only six universities were awarded under the Artemis Student Challenge Program.

Development for the Artemis CubeSat Kit is done by students attending the University of Hawaii at Manoa and supervised by the Hawaii Space Flight Laboratory (HSFL). NASA recognizes the Artemis CubeSat Kit as a foundation enabler in the realm of aerospace engineering education and smallsat commercial launches.

The Artemis CubeSat Kit is unique among other up-and-coming 1U CubeSat kits due to its low-cost, spaceflight readiness, its open-source design, and its educational materials. Multiple organizations are developing 1U CubeSats either as complete products or kits, however, the Artemis CubeSat Kit is the only 1U CubeSat that offers all four points mentioned above. For example, ESAT and MaxIQs CubeSat kits are low-cost, but not spaceflight-ready (MaxIQ, 2022) (Cowley, 2022). Meanwhile, ISiSpace’s 1U CubeSat Bus, Pumpkin’s 1U CubeSat Kit, and Interorbital’s CubeSat 2.0 Kit are spaceflight-ready but not low-cost, proprietary, nor come with educational materials (Cowley, 2022) (Milliron, 2021). Although the Alba Orbital’s Unicorn-2 Satellite Kit and EnduroSat’s 1U CubeSat Platform are spaceflight-ready, the kits have proprietary designs, do not include educational materials, and are priced far above the realm of low cost. (Raychev, 2022) (Walkinshaw, 2021).

This paper presents the technical design of the CubeSat hardware and gives an overview of the educational materials that accompany the Artemis CubeSat Kit. The hardware and software design are discussed to give insight into the capabilities and soundness of design. The online course curriculum in the public domain is described and the topics covered and education methods employed are explained. Finally, lessons learned by the satellite development team are detailed along with other relevant information about the Kit’s development.

**TECHNICAL DESIGN**

**Overview**

The Artemis CubeSat Kit is designed to serve university students, but may be adapted for other audiences, such as middle and high school students (Ngo, 2022). The Artemis CubeSat Kit bus capabilities are outlined in Table 1; these capabilities were chosen to fit most LEO missions.

The satellite hardware consists of five types of printed circuit boards (PCBs) and one 3D printed board: the Payload Board (3D printed), the On-Board Computer (OBC), the Power Distribution Unit (PDU), the Battery Board, the Solar Panel Board and the Antenna board. Figure 2 is an exploded render of the Artemis CubeSat Kit with all the types of PCBs labeled. Figure 6, the system diagram, outlines how the the boards interact with each other. The Battery Board was designed by the PyCubed Team at Stanford University. The rest of the boards were designed by the Artemis team at the University of Hawaii at Manoa.

![Figure 2: Exploded diagram of the Artemis CubeSat Kit. 1: Payload Board, 2: OBC, 3: PDU, 4: Battery Board, 5: Solar Panel Board, 6: Antenna Board](image)

The Artemis CubeSat Kit utilizes HSFL’s open-source mission operations software, Comprehensive Open-architecture Solution for Mission Operations Systems (COSMOS). A simple diagram of COSMOS’s capabilities is shown in Figure 3. COSMOS’s role in the Artemis CubeSat Kit is discussed in greater depth in the Software section. More information on COSMOS is available online (Pilger, 2021). Each of the subsystems
outlined in Table 1 are discussed in the following sections.

![COSMOS capabilities diagram](image)

**Figure 3: COSMOS capabilities diagram**

<table>
<thead>
<tr>
<th>Table 1: Satellite Capabilities</th>
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| **Structure** | - Survive launch and P-POD deployer load conditions  
- Integrate and interface deployment switches  
- Adhere to mass and volume requirements  
- Fasten and secure boards within bus  |
| **Electrical Power Systems** | - Generate power on orbit  
- Regulate power  
- Charge batteries  
- Convert power to 3.3V and 5V  
- Protect against reverse current and AC noise  
- Offer power interfaces for end user payloads  |
| **Communications** | - Send data packets to the ground  
- Receive encrypted commands from the ground  
- Achieve acceptable data transfer rate using Frequency Shift Keying (FSK)  |
| **Thermal** | - Passively maintain safe operable temperatures for components while in orbit  
- Offer active heating to the batteries to prevent quicker discharge  |
| **Attitude** | - Measure position in orbit  |

| Determination Control and Sensing | - Estimate attitude  
- Control attitude in two axes  |
| Command and Data Handling | - Manage information flow between various subsystems  
- Manage reactions to commands from the ground  
- Offer data interfaces for end user payloads  |
| Payload | - Take wide-angle pictures  
- Offer 33mm of space space for end user payloads  |

**Structures and Mechanisms**

The primary structure is made out of black anodized type 3 6061 aluminum, which meets the specifications set by the launch providers participating in the CubeSat Launch Initiative (CSLI). The structure is visible in Figure 2, Figure 4, and Figure 5. Anodization is needed to accommodate surface hardness and roughness requirements. Black anodization was selected to aid the thermal regulation of the bus. Additionally, the structure is able to support 1200 N of force as required by CSLI launch providers.

![Artemis 1U CubeSat with no Solar Panel Boards](image)

**Figure 4: Artemis 1U CubeSat with no Solar Panel Boards. A: Payload Board, B: mock payload, C: OBC, D: PDU, E: Battery Board, F: Antenna Board, G: Antenna**

The structure consists of four pieces: two side panels, one top section, and one bottom section, all of which were designed by the Artemis team at UH Manoa and manufactured through a commercial vendor, Xometry. Figure 5 gives a clear view of two side panels and the
top and bottom sections. The structure’s geometry conforms to the requirements set by the CubeSat Design Specification written by California Polytechnic State University, San Luis Obispo (Cal Poly SLO). The open spaces within the structure allows the end user to have flexibility in stack configuration and payload orientation.

Printed circuit boards are secured using tapped stainless steel rails that run from the top panel to the bottom panel. In Figure 4, the tapped stainless steel tubes pass through the printed circuit boards on the far left and far right sides of the satellite. Aluminum spacers provide structural support to the PCBs by ensuring that the boards do not move during flight. Spacers allow reconfiguration of the stack to adjust the center of gravity of the CubeSat based on the end user’s payload.

![Image](image.png)

**Figure 5: Base and top of the Artemis 1U CubeSat structure on the left, sides of the right**

Mechanisms in the kit include the deployment switches and the antenna deployment system. Deployment switches are installed on the side panels of the structure to allow for indication of deployment from the Poly Picosatellite Orbital Deployer (P-POD). Holes for the deployment switches can be seen on side panels in Figure 5. Many launch providers require deployment switches to act as an electrical safety system and provide the spacecraft with awareness of a deployment event. Deployment awareness is key in allowing safe system startup and antenna deployment after proper separation from the launch vehicle. The antenna deployment system consists of nichrome wire, a small spring, monofilament fishing line, and a spring steel antenna. The antenna is held in its stowed configuration with a monofilament fishing line, tied across a 30 AWG nichrome wire and held taut by a small spring. After the spacecraft is deployed and systems are allowed to start, the power runs through the nichrome wire and burns through the monofilament line to release the spring steel antenna.

**Communication**

To relay satellite information from space to ground, a communication system is necessary. A UHF transceiver in amateur radio frequencies was selected. The Artemis CubeSat Kit utilizes the Hope RF RFM23BP UHF transceiver. This transceiver operates at 433MHz carrier frequency, modulates using Frequency Shift Keying (FSK), and transmits with +30dBm of power with data rates up to 256kbps. End users are able to decide if they want to encrypt transmitted and received signals. Oftentimes, data sent to the ground is left unencrypted while commands received by the spacecraft must be encrypted. Non-encrypted satellite transmissions allow for the RF community to help decode satellite data while preventing external parties from taking control of the satellite and potentially ruining a mission.

To uplink information to the satellite, end users are responsible for managing their own UHF ground station. End users may use their own UHF stations for downlink or the open-source SatNOGS stations may be used.

The RFM23BP has -120dBm receiving sensitivity. There is a 172.69mm by 6.35mm aluminum, quarter-wave monopole antenna for both uplink and downlink. The antenna has 6.32dBi gain. The aluminum antenna is labeled G in Figure 4.

**Thermal**

Most of the electronic components on the bus operate on a wide temperature range, between -40 and 80 degrees Celsius. Due to the wide range of temperatures, most of the satellite bus utilizes passive thermal control. The batteries are the only components on the satellite that need to stay within a tighter temperature band. In order to keep the batteries within their approved temperature range, a Kapton heater is taped to the battery pack. The temperature sensor on the PyCubed Battery Board works in conjunction with the heater to prevent extreme cooling during a mission.
**Attitude Determination, Control, and Sensing**

The Attitude Determination, Control, and Sensing system consists of several sensors and components embedded in the OBC and EPS components. Attitude is determined by current sensors that measure solar panel output, magnetometer measurements from an integrated Inertial Measurement Unit (IMU) on the OBC, and GPS. The GPS generates a position estimate within 2.5 m of accuracy and velocity within 0.1 m/sec of accuracy.

The Kit features active attitude control in the form of torque coils embedded in the solar panels on four faces of the CubeSat. Two center layers of each solar panel board have embedded torque coils to assist in repositioning and stabilizing the satellite. An Eagle render of an embedded torque coil is shown in Figure 7. The system diagram, Figure 6, highlights the torque coil’s relation to other satellite hardware. As the embedded torque coils are only on the four faces of the satellite (see Figure 2), the satellite can only control attitude in two axes. Using the sensor data from the current sensors, IMU, and GPS, Agenent ADCS, a control algorithm within COSMOS, accepts and processes the information on the Raspberry Pi Zero, and sends commands to the PDU that allows current to flow through the torque coils.

**Electrical Power Systems**

The Electrical Power System (EPS) is comprised of three distinct PCBs; the Power Distribution Unit (PDU), the modified PyCubed Battery Board, and the Solar Panel Boards with embedded torque coils. This section covers the elements of each board and its functionality within the kit.

The Solar Panel Board, labeled #5 in Figure 2, is responsible for power generation for the kit. There are four Solar Panel Boards positioned on the vertical sides of the satellite but not on the top and bottom. Each solar panel board has thirty solar cells and, in direct sunlight, each board produces approximately 0.95 Watts. The inner facing side of the solar panel boards houses the interface connectors to connect the solar cells,
temperature sensor, and torque coils to the spacecraft bus.

The PDU, labeled #3 in Figure 2 and C in Figure 4, conducts most of the power management for the satellite. Key features of the PDU include power regulation and switching, accepting and regulating solar power from the solar panels, battery charging, reverse current protection for the system, torque coil controls via H-bridge circuit, remove before flight pin and burn wire activation. The PDU’s interfacing with the satellite is shown in the system diagram, Figure 6. The PDU includes a microprocessor onboard that receives commands from the OBC to perform tasks such as switching the power lines on and off, activating the torque coils and burn wire circuits. Data interfaces connecting to the PDU’s microprocessor are shown in the software diagram in Figure 9. This board has current and temperature sensors to monitor system health. The PDU accepts power coming from the solar panels, regulates charging of the lithium-ion batteries, and converts power from the batteries to switchable 3.3V, 5V, and 12V power lines, which are necessary power sources for various subsystems in the bus and payload. Additionally, the PDU incorporates reverse current protection to prevent avoidable damage to components on orbit and during integration and testing.

The PyCubed Battery Board, labeled #4 in Figure 2, handles power storage. This open-source board was originally designed at Stanford University however, some modifications have been made to the board by the Artemis CubeSat Kit team (Holiday, 2020). Modifications include changes to the grounding scheme and changing the terminal blocks to low-profile connectors. The modified PyCubed Battery Board houses four 18650 lithium-ion batteries in the standard kit configuration and includes charge management circuitry. The circuitry aids in the prevention of short circuits, as well as over-charging, and over-discharging events. It also includes excess charge-current and excess discharge-current protections, which are important for lithium-ion battery longevity and safety.

Command and Data Handling

In the default configuration of the hardware kit, command and data handling primarily occurs on the OBC board, shown in Figure 8, and the PDU. The software diagram in Figure 9 gives visual insight into data flow within the satellite. The OBC serves as an interface and breakout board for the Raspberry Pi Zero, Teensy 4.1, and several other components such as the transceiver, sensors, and end user payloads.

The Teensy functions as the integrated spacecraft controller (ISC) that continuous functions in low power mode. As shown in Figure 9 the Teensy is a central player in internal communications between the OBC and the rest of the spacecraft. Operating at all times during flight, the Teensy 4.1 executes basic functions of the satellite including communication, sensor data collection, and data transfer between components. As an intermediary, information is frequently passed between devices that are connected through the Teensy. An example of the Teensy passing information is when the Raspberry Pi Zero sends attitude adjustment commands through the Teensy 4.1 to the PDU.

![Figure 8: The On-Board Computer](image)

Also located on the OBC is the Raspberry Pi Zero, on the lower right of Figure 8. In relation to the Raspberry Pi Zero, the Teensy 4.1 is a peripheral device. Unlike the Teensy 4.1, the Raspberry Pi Zero is not always on during flight. Due to its high power consumption, the Raspberry Pi Zero cycles on and off based on the current state of the batteries. The Raspberry Pi Zero, along with the Teensy 4.1, may be interfaced with the end user’s payload. The Raspberry Pi Zero interfaces with the Raspberry Pi Camera via the Camera Serial Interface (CSI), as shown in Figure 9. CSI was requested by surveyed end users in the early stages of the hardware kit design. Two of the functions of the Raspberry Pi Zero are packetizing large data sets and handling ADCS data and commands. Both of the
previously mentioned tasks are performed through COSMOS software.

file into a vector of bytes. The vector of bytes will have additional information stored in it so that the vector of

**Software**

The Teensy 4.1 runs an Arduino program, hence the Teensy 4.1 has one continuous program loop running during steady-state operation. The program loop handles tasks such as sensor data collection and receiving commands from the radio or Raspberry Pi, and transmitting information to the ground. Figure 9 gives detailed insight into the Teensy’s power and data connections in the satellite.

The Raspberry Pi Zero runs COSMOS on a Linux operating system and functions as the high level processor on board the spacecraft. COSMOS runs various agents based on the state of the mission. COSMOS agents can be thought of as modular program blocks used to accomplish specific tasks. For example, Agent File Transfer is a COSMOS agent that takes a file that would not normally be sendable and turns the

bytes can be reassembled by Agent File Transfer once received. Agent File Transfer is used when sending payload images from the Raspberry Pi Zero to the Radio to be transmitted to the ground where the image is reassembled.

The PDU’s microprocessor runs a C++ loop very similar to that of the Teensy 4.1. The PDU’s C++ loop will handle power switching operations, reading sensor data, and communicating with the Teensy 4.1. Figure 9 illustrates the data connection between the PDU’s microprocessor and the Teensy 4.1

**Payload**

The hardware kit is designed with the intent that end users are able to interface their payload with little to no adjustments to the hardware. Additionally, the standard kit includes a Raspberry Pi Camera and 3D printed mounting board, referred to as the Payload Board, as the baseline payload. The payload board is visible in Figure 2 and Figure 4. COSMOS is utilized for the
framework of the kit software. COSMOS allows for minimal software development if an original payload is added to the kit.

The satellite contains 33mm of payload space within its 1U aluminum alloy frame for a custom, end user payload. To give perspective, Figure 4 shows a mock payload, labeled B integrated onto a PCB. In order to electrically interface an added payload to the hardware kit, SPI, I2C, and six GPIOs connections are made available to communicate with the RPi. SPI, I2C, five GPIOs, UART, and Ethernet are available to interface with the Teensy. End users should be aware of the characteristics and functions of the RPi and Teensy within the spacecraft bus when choosing how to interface their payload. Switched voltage lines regulated to 3.3V, 5V, and 12V are available for powering added payloads.

DESIGN VERIFICATION

The following sections are dedicated to the steps taken to ensure the Artemis 1U CubeSat meets spaceflight and launch provider standards.

Structure

The Artemis CubeSat Kit structure underwent finite element analysis in SolidWorks to ensure the structure should be able to withstand the loads exerted during launch and deployment. The team also developed a mass budget to ensure the mass of the satellite as a whole is within launch provider requirements. Center of gravity was modeled and found to be within a tolerable range of the geometric center using SolidWorks.

The design of the structure is verified through a series of tests. The first of these tests is the loading test in which.... The second of these tests is proto-flight vibration testing. Proto-flight vibration testing is done on a test kit to ensure workmanship and verify the structural design. The proto-flight vibration profile was selected from NASA GEVS as it will prove that the kit meets standards set by launch providers. A flight readiness vibration test is required by most launch providers once the end user payload is integrated. Figure 10 shows a student preparing an Artemis CubeSat Kit for vibration testing, the kit is in the metal test box which simulates the launch pod and is bolted to the vibration table.

![Figure 10: Vibration testing preparation](image)

Electrical Power System

A power budget was created for the Artemis CubeSat Kit. The team implemented the ISC to act as a low power mode controller.

![Figure 11: Voltage check](image)
During production, solar generation is tested both with HSFL's sun simulator and outdoors on a sunny day. Once power generation is characterized within an expected profile, solar panels are interfaced with the PDU and Battery Board and solar charging is tested. Again, this test is done either outside or with the sun simulator.

For manned missions lithium ion batteries can be a hazard to the astronauts, so there are additional tests needed. In order to enable more space flight opportunities, the lithium-ion batteries are rigorously tested to meet manned space flight standards. Using the NanoRacks Manned Battery Testing Procedures, the team is performing a series of tests that include electrochemical characterization, charge-discharge, a long duration test, three axis vibration tests, and vacuum testing. Batteries are tested by leaving the satellite fully charged in the off state for an extended period of time and measuring the change in battery voltage. As well as vibration testing of the batteries in each axis and the voltages before and after are measured to check for any abnormalities. Figure XXX shows a student measuring the charge on an early version of the Battery Board at the end of a battery test. The remove-before-flight pin, burn wire circuit, and all switches are functionally tested through normal operation on an ESD safe bench. Testing of the H-bridge circuitry is discussed in the Attitude Determination, Control, and Sensing section with the torque coils.

**Communications**

A link budget was created to ensure downlink and uplink are possible with the radio transceiver the team chose and HSFL's ground station. During production, radios are tested by sending information to a miniature ground station, often an SDR interfaced with a laptop, and by receiving information from another radio. Radio testing is done while the satellite is both in flat-sat form and fully assembled.

**Thermal**

Thermal budget tables were developed in order to find the tolerable limits of each component during a LEO mission. The thermal budget allowed for the critical components to be identified. The Artemis 1U CubeSat batteries proved to be the only critical component. As a result, a Kapton heater was implemented to warm the batteries. The team used Thermal Desktop to model the CubeSat's heat distribution while on orbit. Nodes were modeled for each board to identify the temperature changes within the bus and to check if the components are within the allowed temperature range.

During the production phase, the heater and temperature sensor are tested in a thermal vacuum chamber to ensure they are functioning properly and accurately. Thermal vacuum testing validates functionality of components that do not have documented flight heritage. As mentioned above and shown in Figure 12 batteries need to be vacuum tested in order to meet manned battery requirements. Checks are done before and after the vacuum test to verify the dimensions and electrochemical characteristics. This is to check ensure the batteries are safe for a manned space flight mission.

![Figure 12: Vacuum testing batteries](image)

**Attitude Determination and Control Sensing**

Magnetic field sensors in the IMU are tested using permanent magnets. Torque coils in the Solar Panel Board are initially tested by hanging the coils from a fishing line and applying a magnetic field to them to observe visible deflection. Inside a Helmholtz cage, the strength of the torque coils is characterized. Once the torque strength is determined, all sensors and torque coils are used in conjunction in a Helmholtz cage to test the attitude determination and control sensing as a whole unit.
Command and Data Handling

Individual boards’ command and data handling abilities are tested before integration. For example, the PDU’s ability to control torque coils, switch power supplies and measure current will be tested with no other boards interfaced. Once command and data handling has been verified within each board, the entire satellite is integrated together in flat sat form, shown in Figure XXX, and the subsystems are tested again. As a final check, the satellite is fully assembled and standard flight commands are sent to the satellite through the radio. The final check simulates a day in the life of normal operation onboard the satellite. Once the day in the life check passes the satellite’s command and data handling is considered ready. The day in the life test is run once again after the satellite has been vibration tested.

Figure 13: Flat Satellite

Systems Testing

End User Shipment Testing

A fit check is done once all the components are assembled and tested. The fit check ensures that everything in the bus is secured and placed properly.

EDUCATIONAL ASPECT

The intent of the Artemis CubeSat Kit and accompanying curriculum is as follows: Institutions pursue the online curriculum to develop an understanding of the satellite and give instructors a rough lesson plan. When the institution acquires the hardware kit, end users can carry out the physical lab modules. Following the textbook chapter by chapter is like taking a spacecraft mission design course from start to finish. The textbook is a standalone learning guide; an instructor is suggested but not needed. The topics of the textbook are focused on small satellites, aligned with the capabilities of Do-It-Yourself aerospace engineering groups. This Artemis CubeSat Kit is designed primarily for university-level engineering students. However, an adaption of the Kit will be sent out to middle and high school students as a part of the Project POKE program (Ngo, 2022).

As the hardware platform is a 1U CubeSat, the spacecraft design lectures focus on the nuances associated with smallsat design and capabilities. These hands-on sessions are geared toward self-discovery and team communication but have concrete goals with enough structure to inspire progress.

With respect to other online courses, the Artemis CubeSat online course includes a comprehensive amount of course reference material that can aid teams in documenting their design for engineering design reviews. Other courses, whether online or in-person, do not fill the need for an online, interactive, free spacecraft design course, which further has physical lab modules to accompany theory.


“NASA L'Space Academy offers a free, online,
interactive program open to undergraduate STEM students” of which one track is a “Mission Concept Academy” (NASA, 2021). Meanwhile, the course is free (unlike the paid courses), meant for remote distribution (unlike the in-person courses), and focuses on spacecraft bus design and implementation (unlike NASA’s L’Space Academy).

In pursuit of generating a free online textbook, topics from other spacecraft mission design courses and texts relevant to small satellite development were collated. Some notable texts include the CubeSat Handbook by Cappelletti et al., the New SMAD by Wertz et al., Spacecraft Systems Engineering by Fortescue et al., and Space Vehicle Design by Griffin and French (Battistini et al., 2020) (Everett et al., 2011) (Swinerd et al., 2011) (French et al., 2004. These texts are not free and are bound to a physical book format. The Artemis team favors the digital format because digital textbooks can make use of hyperlinks, embedded images, embedded videos, interactive assessments, and interactions with other people. A reader can still download the textbook in static forms, such as PDF, EPUB, MOBI, XHTML, etc., at the cost of the advantages that a web browser platform offers.

Students interacting with the Artemis CubeSat Curriculum are challenged to design a spacecraft mission. Each week, the students will focus on a different subsystem in the classroom and lab. The students will learn about the role of each subsystem, hold the hardware in their hands, and show functionality through demonstrations of the Artemis 1U CubeSat. The course progressively builds in complexity by sectioning the spacecraft into subsystems and blending the theory and physical systems on a weekly basis. Students will form teams and begin a condensed version of the formal review process conducted in industry and at NASA centers. The processes include Concept, Design, and Readiness Reviews. The CubeSat kit gives students design-realistic constraints. Lab modules offer experience integrating components and debugging issues. Students will finalize their design and move toward testing. While student teams drive the mission topic, the educational materials will offer individualized, specific support from combined decades of spacecraft experience.

Students taking the Artemis course are expected to modify the basic CubeSat to meet a proposed mission’s requirements, be it integrating a hardware component or developing an innovative section of software. As the course comes to an end, each student team will present a fully functioning cubesat in the Flight Readiness Review. The course will close with a lessons-learned session and choose a subset of the projects to transition to long-term projects, CubeSat Launch Initiative (CSLI) proposals, potential papers, and features in the online course.

Upon implementation at the University of Hawaii at Manoa, the course received the following feedback: (i) the course content was at the appropriate level for non-affiliated engineering students to gain a basic understanding of how to design spacecraft; (ii) the course activities of reading the textbook, reinforcing with lectures, watching experts demo tools, working through individual labs, and working with a group on a project were all valuable to the course; (iii) the interactive software and hardware labs were realistic and fun. Many students voiced that this course was one of their favorite courses and they learned quite a bit.

There are no required prerequisites for the course but any bit of background knowledge and skills helps. The more knowledge and skills a student begins with, the more easily and faster the student will get through the course. The less knowledge and skills, the more the student has to stop and learn foundational skills to catch up. The following skills will come up frequently during the curriculum: C++, Linux terminal basics, soldering, Kirchoff’s laws, Autodesk Eagle, and multimeter use.

**Textbook**

Dr. Frances Zhu and the Artemis CubeSat Kit team developed the previously mentioned open-source, free, online textbook to bring the knowledge of spacecraft mission design to as many people as possible. This resource is free, as originally proposed to the NASA Artemis Student Challenge (Bridenstine, 2020). The goal of the Artemis CubeSat Kit, including the educational accessibility tools, is to provide a low cost, easily accessible entry to space science research. Breaking down the traditional barriers and using technology like the Pressbook platform fosters diversity and inspires creativity thus pushing the boundaries of knowledge.
The textbook is intended to be a comprehensive resource for those interested in low earth orbit (LEO) mission design concepts for small satellites. It starts with a brief context description of spaceflight with details on history, future, players in the field, modern application, general defining features of a spacecraft, and a rough overview of the spacecraft creation process. The textbook covers background information of systems engineering including requirements, an overview of spacecraft subsystems, and driving forces of spacecraft design. Space environment details and their effects on the spacecraft are covered. Orbital mechanics are covered and different orbit types and their effect on spaceflight missions are highlighted.

The textbook shifts focus to spacecraft design. Structures are discussed with key points being typical requirements, design drivers, general arrangements, common configurations, and structural analysis. Power generation and management are covered with emphasis on typical requirements, general arrangements, space energy sources (and orbital effects on the energy sources), solar arrays (their efficiency and degradation), batteries, and power budgets. Telecommunication topics are covered, the textbook discusses telemetry, ranging, ground stations, frequency and modulation selection, antennas, and link budgets for RF communications systems.

Topics covered relating to thermal control are fundamentals of heat transfer, active versus passive heat control, thermal analysis (including radiation and finite-element modeling), and thermal vacuum testing. Attitude determination and control testing is covered with an emphasis on dynamics, modes, determination and control; typical requirements, and design drivers.

Command and data handling is discussed and centered around common configurations, spacecraft computers, memory, storage, data buses, flight simulation, and data budgeting. When it comes to system realization, integration, verification, validation, fabrication, vibration testing, thermal testing, other testing methods, and launch vehicle integration are covered. The textbook is accompanied by software tutorials which include the Artemis User Manual (a comprehensive user manual on all the satellite’s systems), Arduino Libraries, COSMOS documentation and COSMOS compilation tutorials.

**Lab Modules**

The lab modules and software tutorials serve as exercises within the curriculum and can be found at the end of each textbook chapter. Each subsystem has a digital lab based in software and a physical lab requiring the hardware satellite kit.

![Figure 14: Assembled Artemis CubeSat Kit and M2 hex screwdriver](image)

The structures subsystem labs include modifying the OnShape CAD to reflect the team mission, analyzing the structure under realistic loads in a finite element analysis software, and collating a mass budget. The physical portion of the structures labs includes structural assembly inspection, compression loading, and burn wire deployment simulation. Figure 14 depicts an assembled Artemis CubeSat structure ready for inspection and loading tests.

![Figure 15: Battery Board and digital multimeter](image)
The software lab for the electrical power systems includes creating a power budget and using Systems Tool Kit to calculate solar panel generation to inform a power profile analysis. The physical lab for the electrical power system allows students to assemble the charging circuit subsystem, measure the state and rate of charge, and characterize solar panel performance. In Figure 15 a student is measuring the state of charge on the Battery Board.

**Figure 16: Cubic SDR (a software defined radio application) with FSK beacons visible in the center of the waterfall plot**

The software section of the communications lab includes filling out a pre-made link budget spreadsheet that calculates the uplink and downlink margins. The physical lab has students test the satellite’s radio by sending messages over the air from the satellite’s radio and receiving them on a software defined radio (SDR), known as the RTL-SDR, and visualizing them using an SDR software called Cubic SDR. Figure 16 is a screenshot of Cubic SDR from the communications lab. In the screenshot, data packets are visible in the waterfall plot.

**Figure 17: Power Supply, Artemis CubeSat, heaters, and wireless thermometer**

The software section of the thermal control labs has students create a heat transfer budget and perform finite element analysis on how to generate temperature profiles via Autodesk Thermal Desktop. The physical portion of the thermal lab demonstrates and characterizes the functionality of the Kapton battery heater. Figure 17, shows a Kapton heater ready for testing with a contactless thermometer, an Artemis 1U CubeSat, and a DC power supply also visible. The students retrieve and visualize data from the solar panel temperature sensors under lamp-light simulation.

**Figure 18: Solar Panel Board with activated torque coil interacting with a magnet.**

The software portion of attitude determination and control lab tasks the students with simulating attitude dynamics in python notebooks along with a pointing budget. The ADCS physical lab has students test the satellite’s torque coils by hanging them in the air and activating the torque coils. Figure 18, shows students testing torque coils with a permanent magnet.

**Figure 19: COSMOS Web Data Visualization**

The software portion of the command and data handling labs has students install COSMOS and COSMOS Web onto their computers and complete a data budget. COSMOS Web data visualization is shown in Figure
19. The physical lab has students collect data from the satellite’s sensors using COSMOS Web. Students observe GPS, IMU, current, temperature, and voltage data from the satellite. If time is available, students can collect data from the Raspberry Pi Camera and measure data transfer times.

**Online Course Materials**

An openly accessible Google Drive contains online course materials that self-guide a semester-long course that meets three times a week at an hour per meeting.

A sample course activities and assignments schedule spreadsheet, shown in Figure 20, has multiple tabs. A schedule helps keep the smallest educational experience at a pace that is contained to a semester. The assignment arc tab outlines the intention behind the sequence of assignments. The assignment tabs record the day assigned, due date, estimated time to complete, links to grading rubrics, and the assignment task with embedded documents. This particular course activities spreadsheet was implemented in 2021 and does not have physical labs scheduled in lieu of completing a second design cycle, whereas the 2022 implementation has physical labs scheduled at the sacrifice of only completing one design cycle.

All lecture slides and recordings of lectures are in a Google Drive folder such that students can refer to slide decks and video recordings for assignments or the group project. This folder is pictured in Figure 21 and an example of the contents of one of the lectures is shown in Figure 22.

**Post-lab assignments** reinforce the concepts that should be covered in the digital and hardware labs.

Datasheets of components used in the Artemis CubeSat Kit are also shared for reference in the design process.

**Budget templates**, such as the one shown in Figure 23, for each subsystem are distributed as a starting point for mission design.
**DISCUSSION**

To give perspective on some of the lessons learned, the team structure and the circumstances of the project’s development are presented.

**Team Structure**

The Artemis CubeSat Kit Project began with a team of 4 undergraduate students and 4 technical advisors, one of which is the program director. As the project progressed, two full-time junior engineers were added to the team. The junior engineers were individuals who recently graduated with a bachelor’s degree. Two part-time graduate students joined the project for their graduate thesis. Throughout the project there have been around three to five interns, students at UH who are actively involved in the project and receive either pay or credits for their time. There are also students who participate through a Vertically Integrated Project (VIP) framework, inspired by the Georgia Tech model; these students usually contributed three to six hours a week and participated for at least one semester. Technical mentors were available to answer questions but in general did not participate on the project.

The mentors, junior engineers, and graduate students have remained on the project consistently since their joining. The interns and VIP students join and leave depending on interest and school schedule.

**Team Turnover**

The team quickly learned that documentation is one of the best practices a team can have when anticipating high member turnover. In the beginning, the documentation was lacking and unorganized. Whenever a new student was onboarded, one of the junior engineers or advisors would have to work with them for quite some time before they were able to take off on their own. They have worked hard not only making quality documentation but organizing in a logical and intuitive way. Now, new students have a much better understanding of their role and technical context after reading the documentation from previous students which allows them to continue previous work.

**COVID-19 Impacts**

The Artemis CubeSat Kit project was funded shortly after the COVID-19 pandemic lockdowns began. As a consequence, only select personnel were allowed in the lab. This offered unique challenges to onboarding, meetings, and collaboration as a whole. To overcome these challenges the team switched to zoom-based meetings and limited the number of students in the lab. However, limiting the number of students in the lab meant that the team could not rely on undergraduates nearly as much as usual. It also meant that onboarding was almost completely put on hold, mostly during the pre-vaccine era of the pandemic.

Throughout COVID-19 and especially in the early stages, electronic components have been difficult to get, shipping has been slowed, and PCB manufacturing has been delayed. In some cases, manufacturing has been halted completely. These problems in the supply chain have naturally slowed development. The team has had to make multiple redesigns simply because an essential part would go out of stock and effectively disappear.

To counter supply chain issues when designing printed circuit boards, the team learned that having multiple review sessions can save future redesigns. The team learned that the only time a bill of materials should be made is the minute before the order is placed because parts go out of stock continually and frequently.

**Interfacing Design with Personnel**
The team learned that clear and well-distributed functionality statements can save redesign time. While a graduate student might have a clear idea of what a printed board needs to accomplish, if the person fabricating the board does not realize for example that a component needs to be I2C and SPI compatible, they might end up with a component that is only I2C compatible. Queue unhappy redesign.

One might think that the hardware team should design the boards and the software team should write programs independently in a modular fashion, but this lead to interfacing problems. The software team absolutely must be involved in the hardware design because the avionics team is thinking about the physical hardware connections, such as a UART1 TX connection to UART1 RX. The software team thinks about master-slave architecture, data transfer rate, and data storage and these dependencies rely on the avionics design. As a simple example, the avionics team might connect a camera to a processor through UART not knowing that the available UART speed is 9600 baud which translates to a comically long transfer time. This example demonstrates a case where a printed circuit board with any sort of programmable element needs to be created with someone who knows how to program.

CONCLUSION

The Artemis 1U CubeSat Kit is a simple and robust CubeSat kit. The Kit will remain open-source, with all of its designs in the public domain. End users are welcome to build the kit themselves or purchase it from the University of Hawaii pre-fabricated. The Artemis CubeSat Kit is a University of Hawaii maintained project; the team continuously updates the hardware design and software modules to suit the needs of the community.

Already, the Artemis CubeSat kit has served as a unique, hands-on learning experience to the design team. During development, the team applied knowledge, such as evaluating the power budget or running thermal simulations and developed skills, such as writing an end user agreements and interfacing with vendors. The Artemis team believes the Artemis CubeSat Kit offers a similarly unique educational experience to end users. The Kit is intended to allow universities to skip the time-consuming bus design, testing, and production and instead skip straight to the payload and mission design. The Artemis CubeSat Kit significantly lowers the financial and technological cost of entry into the realm of aerospace engineering for most institutions.

The textbook and lesson modules, available for free online, streamline the teaching and learning about small satellites for both teachers and students. The provided course materials better aid students’ understanding of satellite design and allow students a body of knowledge to fall back on while getting situated in aerospace engineering. Furthermore, the lesson plans give teachers a clear path to teach the expanse of difficult topics in the span of one semester. The textbook also helps teachers who have limited knowledge of aerospace engineering.

The hope is that the Artemis CubeSat Kit will increase the number of universities with a hands-on approach to aerospace engineering and the number of universities with aerospace engineering in general.

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References


