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Ke Ao: A Low-Cost 1U CubeSat for Aerospace Education and Research in Hawaii

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ABSTRACT

The Ke Ao satellite is a low-cost 1U CubeSat designed and developed by an undergraduate team of engineering students at the University of Hawaii at Manoa (UHM) in collaboration with the Hawaii Space Flight Laboratory (HSFL). The primary goal of the mission is to take one or more pictures from space and automatically identify the Hawaiian Islands using Machine Learning Algorithms - this will demonstrate improved onboard operational autonomy in space. A secondary goal of this project is to promote Aerospace Education and Workforce training in Hawaii. The Ke Ao project was inspired by the Hiapo CubeSat initiative of the Hawaii Science and Technology Museum as a unique platform used to provide engaging meaningful hands-on STEM curriculum for Hawaii students K-12. The realization that low-cost flight hardware, in the order of ~$10k, is practically non-existent, and therefore the barrier to launch a flight-capable CubeSat is still high for small organizations and schools with low budgets. The Ke Ao project started in the Fall of 2019 with the Vertically Integrated Project (VIP) Aerospace Technologies with Electrical, Mechanical, and Computer Science Engineering Students at UH and continued to be facilitated under the Mechanical Engineering Senior Design Course within the College of Engineering throughout the year of 2020. The project was impacted by the global COVID-19 pandemic but this enabled the student team to improve on the design and simulations. Hiapo and Ke Ao also inspired the NASA Artemis CubeSat Kit project being developed at the HSFL. The Artemis CubeSat Kit will be used as an educational tool for teaching aerospace and distribution in the public domain. The development of these three CubeSats allowed for synergistic development and multipurpose designs and gave the students a wide breadth of design experiences. This paper will expand on the design and development for the main objectives for Ke Ao (1) take one or more pictures of the Hawaiian Islands from space; (2) cost shall be no more than $10,000 with built parts; and (3) launch-ready via the NASA CSLI application and requirements. To address these objectives Ke Ao uses spaceflight capable but low-cost hardware flown in previous CubeSat missions and consists of seven primary subsystems: Attitude Determination and Control System, Communications, Electrical Power Systems, On-Board Computer and Flight Software, Payload, Structure and Mechanisms, and Thermal Control Systems. Ke Ao will use onboard magnetic torquers to control the attitude of the payload and take pictures of the Hawaiian Islands. The data will be transmitted to the HSFL ground stations in Hawaii and through the SatNOGS ground station network across the World. Ke Ao's mission and primary goals are in line with the 2018 NASA Strategic Plan's Strategic Objective 3.3 to Inspire and Engage the Public in Aeronautics, Space, and Science and contribute to the Nation's science literacy.

INTRODUCTION

The Ke Ao mission is a 1U CubeSat being developed by the UHM College of Engineering (COE) Students in collaboration and mentorship with the HSFL engineers. This CubeSat leverages from various lessons learned from HSFL's Neutron-1 3U CubeSat [1] and 6U NASA HyTI mission [2] that are developed by HSFL. A rendering of the Ke Ao CubeSat is shown in Figure 1. The satellite will take pictures of the Hawaiian Islands from Low Earth Orbit (LEO) using automated image capturing using machine learning algorithms. The spacecraft bus will be integrated and tested at the HSFL facilities. The payload is a CMOS Gumstix Caspa VL fisheye camera with flight heritage from the JPL-led MarCO CubeSat mission [3]. Ke Ao is expected to be ready to deliver by Spring 2022 and expected to launch in Fall 2022. Different launch opportunities are being pursued including the NASA CSLI program to launch from the ISS. The current design assumes Ke Ao is deployed from the ISS with an approximately circular orbit at ~400km with 51.6 degrees inclination.

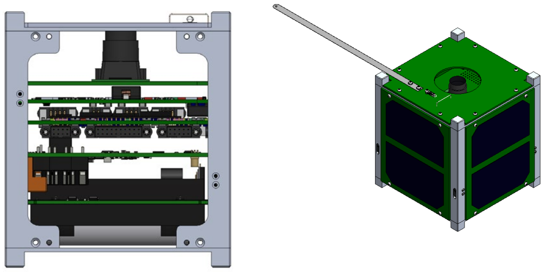

Figure 1: Rendering of the Ke Ao 1U CubeSat

The project involves more than 30 students of varying levels and degrees from Mechanical Engineering, Electrical Engineering, and Computer Science. Through the extensive involvement of the students developing Ke Ao is providing valuable training for the next generation of space engineers. The Ke Ao project was initially inspired by the Hiapo CubeSat initiative of the Hawaii Science and Technology Museum as a unique platform used to provide engaging meaningful hands-on STEM curriculum for Hawaii students K-12 [7, 8]. Hiapo and Ke Ao also inspired the NASA Artemis CubeSat Kit project being developed at the HSFL. The Artemis CubeSat Kit will be used as an educational tool for teaching aerospace and distribution in the public domain [9, 10]. Ke Ao's Mission Statement is "*Ke Ao is a low-cost, 1U CubeSat with the goal to take pictures of Hawaii from space to promote aerospace workforce training and education in Hawaii*."

Ke Ao's main mission requirements are:

- Shall be able to take at least one picture of Hawaii from space
- Shall be a 1U CubeSat
- Shall not cost more than $10,000
- Shall comply with CSCLI requirements [4]
- Shall survive and operate in space for two months or more
- Shall use the HSFL COSMOS software for ground station & flight ops software

Significance and Impact

Ke Ao was started as a Vertically Integrated Project with students from the COE to promote Aerospace Education in Hawaii. The progress made on Ke Ao during the pandemic had to be significantly de-soped and re-adjusted with the students but the design and model simulations continued to mature the design. Ke Ao is now expected to be flight ready in 2022. As goals for the project were scaled back, a more complete set of simulations that validated the mission design were developed, to prepare for integration and testing, during 2021. Ke Ao ultimately will be a technical reference CubeSat with documented guidance. The completion of Ke Ao allows future students at UHM to refer to the legacy of the project, continue to improve on the designs, and support other educational projects, as evidenced with the Artemis CubeSat Kit project.

The Ke Ao Senior Design Team worked with the VIP team, HSFL, COE, and sponsors in the community to sponsor the Ke Ao project. The other UHM 1U CubeSat projects worked in synergy with the Ke Ao project as designs, testing, and results were exchanged during the development process. This collaboration effort proved to be very successful to help the students share learned experiences across projects and improve on a shared design.

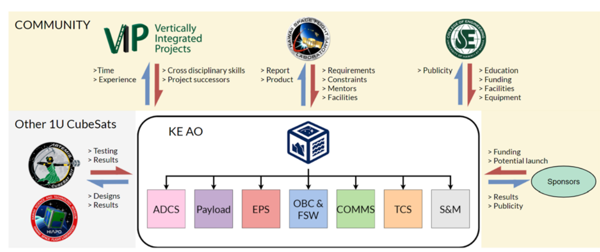

Figure 2: The system architecture of the Ke Ao project. This shows both internal and external interactions and stakeholders.

SYSTEMS ENGINEERING

Mission Design

Ke Ao is designed according to the 1U CubeSat Design Specification [5], the NASA CSLI Launch Services Program (LSP) requirements [4], and the NanoRacks CubeSat Deployer (NRCSD) requirements [6]. Besides the program level, launch, and deployment requirements, the main mission requirements are as follows:

1. Ke Ao shall be 3-axis stabilized and be capable of orienting the camera aperture to take pictures of the target area (default target is Hawaiian Island Chain).
2. The Attitude Determination and Control System (ADCS) shall provide a pointing accuracy of ± 8° or better to fit the main Islands of Hawaii within the FOV.
3. The HSFL On-Board Computer (OBC) shall store and forward the camera data to the ground and include a redundant data channel.

Overall System Architecture

To support the payload camera the Ke Ao bus system includes the primary OBC that serves to control the camera functions and to store and forward the data to the ground. The Electronic Power System (EPS) provides switchable power to the various systems in the bus and it charges lithium-ion batteries with five body-mounted solar panels. The ADCS provides the 3-axis system stabilization to perform the imaging events. Finally, the RF Communication (COMM) system uses one primary radio to transfer the payload data. The payload data is transferred down via a UHF channel alongside the command and control of the spacecraft is executed via the same radio channel. Figure 3 shows the overall system diagram.

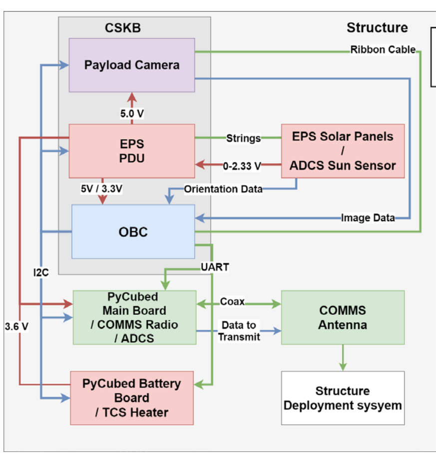

Figure 3: Ke Ao System Level Block Diagram

SPACECRAFT BUS

The Ke Ao spacecraft bus includes a 1U CubeSat structure, an EPS with five body-mounted solar panels and a Li-Ion battery, OBCS with a low power microcontroller and an ARM processor for payload data management, thermal management, a 3-axis stabilized ADCS, and COMM. An exploded view of the spacecraft with the main functional components is detailed in Figure 4.

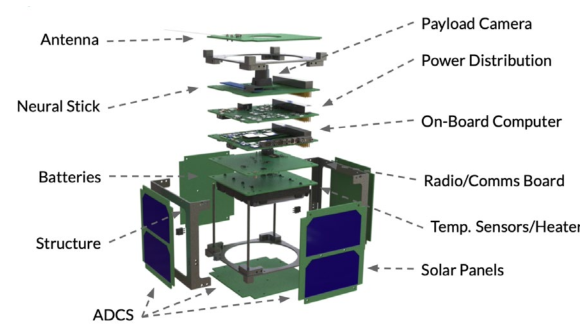

Figure 4: Ke Ao exploded view detailing main components

Structures and Mechanisms

The Ke Ao structure is shown below in Figure 5. The structure consists of four aluminum panels that make up the load-bearing frame. There are four stainless steel rods mounted to the base of the frame that the PCBs (printed circuit boards) of the satellite are placed on. There are four deployment switches along the rails of the structure (three are typically required by launch providers). The top panel has a PCB mounted to the exterior with an antenna and antenna deployment mechanism attached. All panels and switches are fixed with stainless steel screws.

The frame panels are designed to be made of milled 6061 aluminum with level three anodized surfaces (to meet NASA's material requirements for spacecraft [11]). The aluminum is milled to meet the tolerance required by the typical CubeSat deployers. A drawback to using aluminum is that it has to be level three anodized to meet the hardness and surface roughness levels to pass launcher requirements and unfortunately Aluminum anodization is not available at shops in Hawaii.

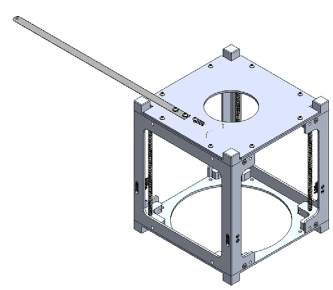

Figure 5: Ke Ao structure assembly in SolidWorks. Page up is the positive z-direction.

The antenna of the satellite is made of 1095 spring steel so that it can be bent around the satellite in order to fit in the deployer. The bent antenna is held in place by a nylon line attached to a spring. The nylon line is held in tension over a nichrome wire. After being deployed the main board of the satellite can power the nichrome wire which will melt the nylon line and the antenna will be extended.

The fasteners in the Ke Ao structure are metric stainless steel screws. The PCB and switches are held in by nuts. All other screws are threaded into the frame which will have threaded inserts. Threaded inserts were used whenever threading into aluminum because aluminum is soft compared to stainless steel and the threads may wear and strip if the structure needs to be reassembled. The team anticipates the structure to be reassembled as it is to be for education and may be taken apart to inform students on its design. All fasteners will be installed and torqued to NASA's torque specifications found in NASA MSFC-STD-486-B [11].

Thermal

The spacecraft will orbit in LEO where principal sources of heat are the Sun, Earth, and internal powered components depending upon the operational modes. The cold temperature of deep space balances the temperatures on the satellite. The thermal operational range requirements for avionic components are between 0°C to +55°C. The main internal heat sources are the computers (15 mW for the PyCubed, 2.5W for the HSFL OBC), radio (0.1W), and the payload camera (0.3W).

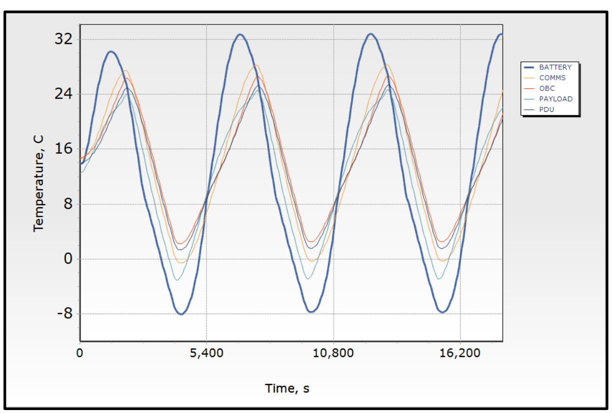

Figure 6: Thermal Desktop model for Ke Ao shows temperature range between -8 and +35 deg C.

The thermal subsystem is tasked with regulating the temperature of the CubeSat. Ke Ao will use an active system composed of a Kapton (flexible polyimide) electric heater attached to the batteries and temperature sensors placed on each board. According to thermal simulations done in Thermal Desktop, the heater needs to be capable of providing 1.5 watts of heat to the batteries during cold cycles of the orbit to meet all thermal functional requirements. Figure 7 is a thermal subsystem diagram showing how the TCS works.

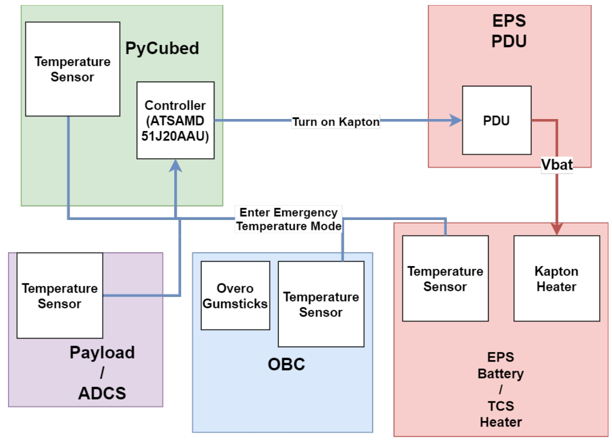

Figure 7: Ke Ao Thermal Subsystem Block Diagram

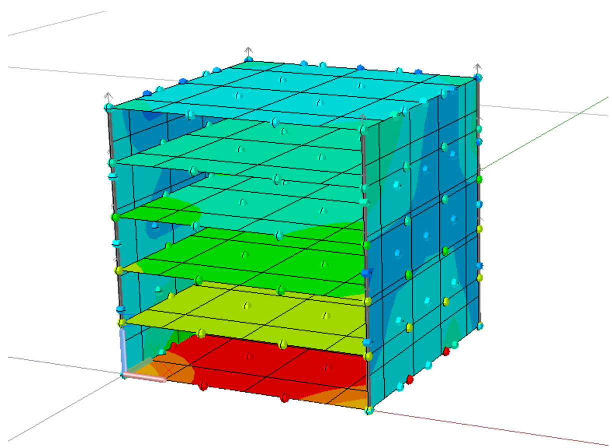

Figure 8: Baseline Thermal Desktop model of Ke Ao avionics.

On-board Computer Subsystem

HSFL has developed the main flight computer for the Ke Ao mission based on a COTS available ARM processor board as shown in Figure 9 [1]. The COTS board model is the Gumstix Overo IronSTORM-Y which was recently successfully flown on the NASA Mars Cube One (MarCO) CubeSats [3]. The computer is based on the Extended temperature Texas Instruments DaVinci DM3730 Applications Processor with a base clock capable of running up to 1GHz. It includes a 512 NAND Flash memory with the option to dual boot. The OBC is able to connect to CubeSat via the CSK connector bus using the standard interfaces. The main features of the HSFL OBC board are the 4 port UART device to enable more devices to be connected via serial. This device allows communications up to 921600 baud. The other main feature is the ETH device to enable Ground Support Equipment (GSE) connectivity and/or node-to-node connectivity for redundant on board computer architectures.

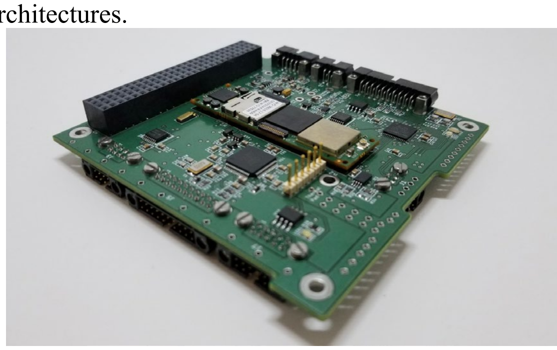

Figure 9: HSFL On Board Computer v3.3 (wifi antenna is not used in-flight version)

The second component used in the On-Board Computer is the PyCubed board [12,13]. The PyCubed board is an all-purpose low cost circuit board. It houses a Microchip ATSAMD51 microcontroller, an RFM98W radio, imu, gps, solar panel and burn wire headers, along with a battery board that is compatible with the mainboard. Software on the board is run using Micropython and base files are provided for the board. The PyCubed board is able to run on low power at 0.013 W.

The PyCubed software is run using Micropython. Python scripts are written for all hardware components on the PyCubed board. This includes the radio, IMU, GPS, power monitor, batteries, and one to deal with communications with the HSFL OBC.

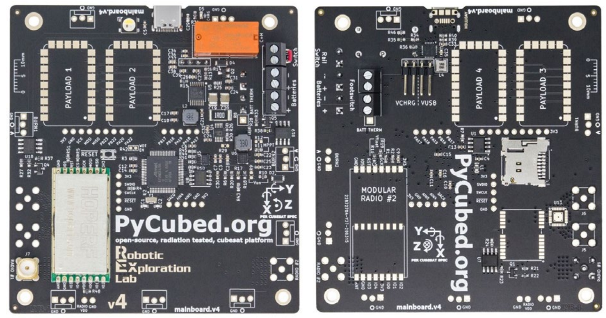

Figure 10: PyCubed Mainboard

A "main.py" file is then used to control the board when powered on. The main file can be used to transfer messages over the radio or get readings from certain components. The software diagram is shown below. The main software agents are on the HSFL OBC (blue box on the left), while the PyCubed contains and controls hardware such as the IMU, GPS, radio, and power monitor (pictured on the right). Most connections are made over a SPI or UART port. The camera is connected by a CSI cable to the HSFL OBC.

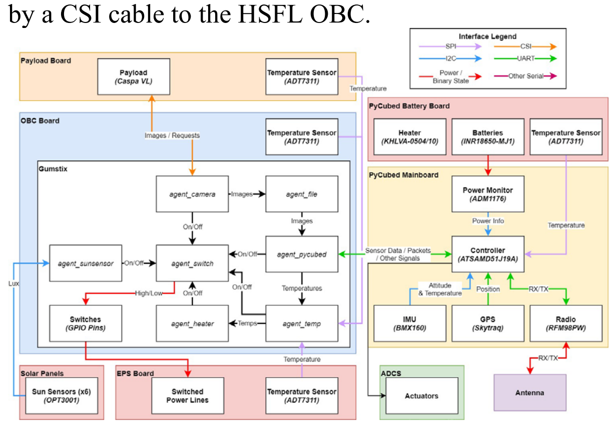

Figure 11: Ke Ao Software Diagram

Electrical Power Subsystem (EPS)

The EPS is designed to generate, store, and distribute power to Ke Ao. It is composed of body-mounted solar panels, batteries and a battery board, and a power distribution board. The solar panels are designed to generate power from the sun and send it to the power distribution board and batteries. The power distribution board is designed to send the generated power to the spacecraft bus. The excess power generated by Ke Ao will be stored in the batteries mounted on the PyCubed battery board.

The five solar panels are made of standard PCB boards and are mounted to five exterior panels on each side of the cube satellite. These panels are designed to connect two solar cells in series. The access panel on the side of Ke Ao only houses one solar cell in order to leave room for the access port. There are no solar panels on the top of Ke Ao which houses the camera, so the view will not be obstructed. The space-rated gallium arsenide (GaAs) solar cells made by the EMCORE corporation are used in order to achieve the highest efficiency possible when converting sunlight to electrical energy. The EMCORE solar cells have an efficiency of 28% and are extremely light with a weight of approximately 0.033 grams. These solar cells have a voltage and current at max power of 2.33V and 0.434A respectively. The max power output of each cell is approximately 1.01W. Each solar panel with two solar cells has a max power output of approximately 2.02W.

The configuration of the five panels is shown in Figure 12.

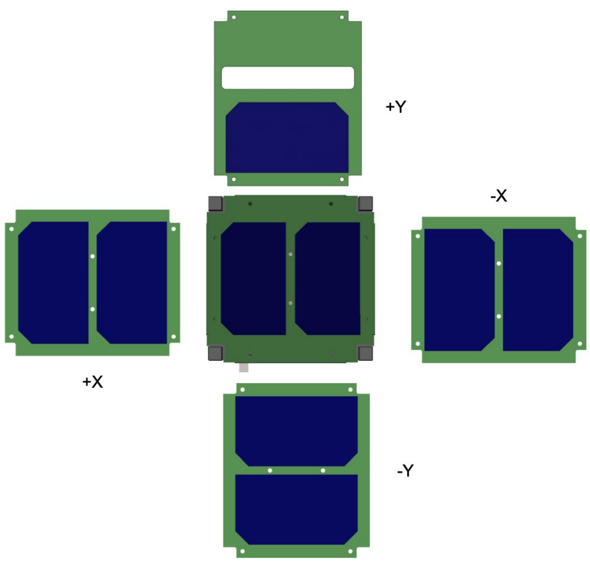

Figure 12: Body mounted solar panel arrangement

The expected tumbling rate coming out of the deployer is 1 to 2 deg/sec, thus the rate used in the power simulation was 1.5 deg/sec. The average power generated in nominal mode is ~2.5W. The average power consumption is ~0.5W over the 90 min orbit. This produces a positive net power usage so that the battery can be slightly over time. Figure 13 and 14 shows the overall battery capacity increase over a period of one orbit while the spacecraft is taking science data and transmitting it to the ground.

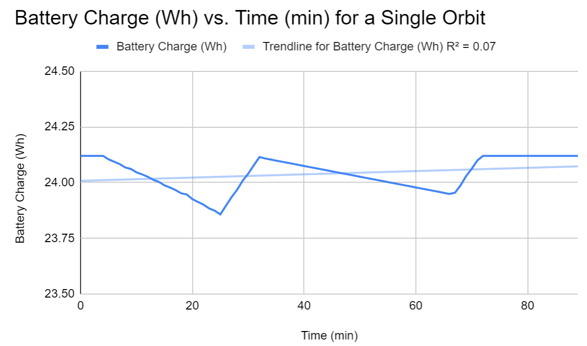

Figure 13: Power simulation for battery charge over a sample orbit.

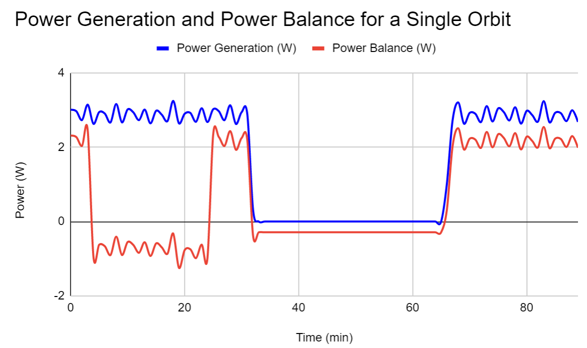

Figure 14: Power simulation for battery power balance.

Ke Ao utilizes the PyCubed battery board which has been used on previous space missions [12,13] and is designed to fit up to six 18650 batteries at max capacity. The battery balancing and power regulation through the battery board are controlled by the PyCubed mainboard. The PyCubed battery board is designed to have a 2S3P battery configuration with two batteries connected in series and three sets are connected in parallel. Ke Ao will use four Samsung INR 18650-35E batteries which give a total energy capacity of approximately 24 Wh. The Samsung batteries have a nominal voltage of 3.6V and energy capacity of 3350mAh. The battery pack has nominal operating voltage of 7.6V. The total weight of the populated battery board with four cells is approximately 200 grams. To comply with manned flight launch requirements [14], the battery features multiple high-side and low-side solid-state inhibits as well as voltage, current, and temperature telemetries to monitor battery operation.

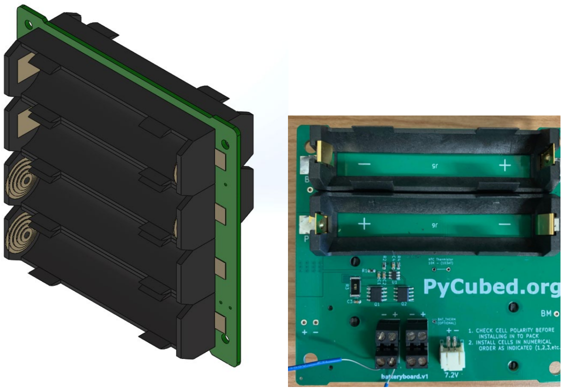

Figure 15: (Left) Isometric CAD model of the PyCubed battery board. (Right): Front of PyCubed battery board.

Attitude Determination and Control Subsystem (ADCS)

The ADCS subsystem's role is to point Ke Ao to the primary target location, the Hawaiian Islands. To do this, the ADCS works with the OBC and EPS as shown in Figure 16. The OBC collects sensor measurements from the attitude sensors (IMU, GPS, and sun sensors) and payload camera to determine the satellite's attitude. Once the OBC determines the attitude, a command is sent to the PDU to turn on/off the actuators (torque coils). Turning on the actuators allows the satellite to rotate its orientation for pointing. This is done until the payload's viewing angle is in range of the target location.

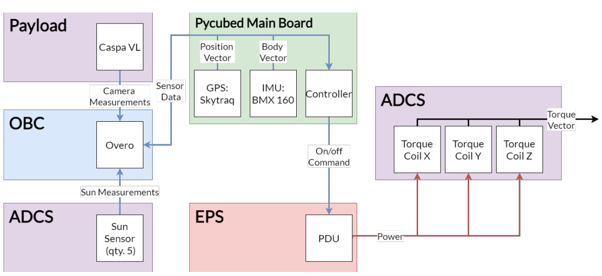

Figure 16: Ke Ao ADCS Subsystem Block Diagram

The ADCS design consists of two main components, attitude determination and actuation. Photodiodes/optical sensors, IMU (BMX 160), and GPS (SkyTraq Venus838LP) are used to collect measurements for attitude determination. The photodiodes/optical sensors are found on each solar panel and take measurements of the sun. The IMU and GPS are located on the PyCubed mainboard to take measurements of the satellite's body rates (magnetic field, angular rates, acceleration/G-forces) and position respectively. The specified IMU have flight heritage on KickSat [15]. Sensors that have no flight heritage are subject to environmental testing to ensure operation during the mission. Sensor measurements are used in a propagator/flight software within COSMOS to determine the satellite's attitude. Embedded coils were designed to actuate the satellite's orientation as it offered the least volume and cost amongst the other options. It is typical for 1U CubeSats to not have an active ADCS due to insufficient volume [16] but embedded coils in the solar panels can be an effective way to implement actuator designs. The embedded coils are also designed to also adjust the magnetic torque by switching between the circuits in series and parallel configurations. The calculated torque using a single embedded coil is 2.33E-06 N•m and increases as more layers are placed in the solar panel. The sensor measurements are combined using an extended Kalman filter and used with control algorithms for 3-axis pointing (including Earth target tracking, Sun tracking, inertial pointing, etc.).

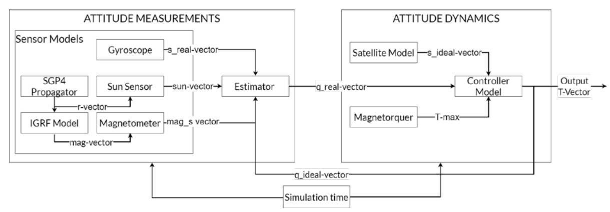

Figure 17: Mindmap of the ADCS model detailing the attitude dynamics and measurements

The following attitude control simulation results, shown in Figure 14, are obtained using an ISS representative orbit (401 x 408 km) with an inclination of 51.64° and an orbital period of 92 min.

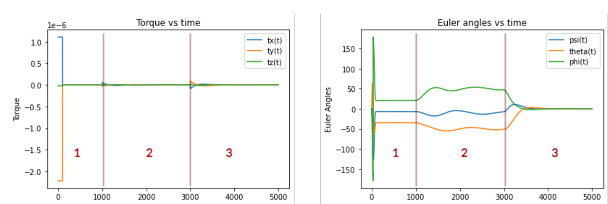

Figure 18: True RPY attitude angles during detumbling and sample pointing sequence

Communications

Ke Ao's radio is housed on the PyCubed Mainboard. It uses an RFM98W-433S2 (low power, long-range, surface mount transceiver) from HopeRF. It is capable of using Long Range (LoRa), Frequency-shift keying (FSK), Gaussian Frequency Shift Keying (GFSK), Gaussian Minimum Shift Keying (GMSK), or On-Off Keying (OOK) modulation. The radio is low-cost as well as having minimal mass at only 0.75 grams. As the Ke Ao team learned more about the SatNOGS ground stations network it was determined that the FSK modulation would provide best results. SatNOGS is a global network of satellite ground stations. With the use of SatNOGS, data download from Ke Ao is no longer limited to just when it is orbiting above Hawaii. This grants more opportunities for communication with Ke Ao. Ke Ao uses the annotated AMSAT/IARU link budget created by Radio Amateur Satellite Corporation. The link budget system follows recommendation P.341-7 from the Radiocommunication sector of the International Telecommunication Union. This discusses the concepts and equations used in transmission loss for radio links.

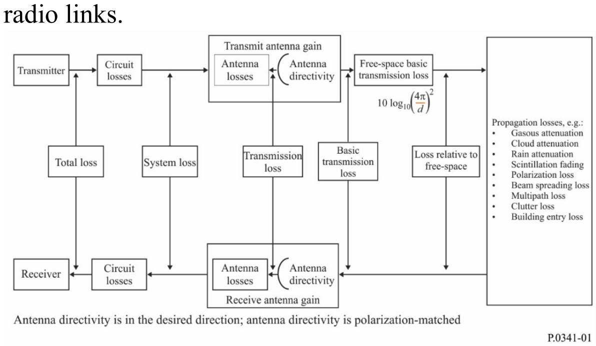

Figure 19: Graphical depiction of terms used in transmission loss concept

Payload System

The payload imager is tasked with performing the main mission of Ke Ao, to take pictures of Hawaii from space (or other given targets). The camera selected is the Caspa VL from Gumstix, seen in Figure 20.

Figure 20: Caspa VL camera, selected as payload for Ke Ao (left). KLB-0360 camera lens included with Caspa VL camera from Gumstix.com (right).

The Caspa VL is at the lower end of the spectrum of camera options considered, having a cost of less than $100. Given that Ke Ao is a project that aims to be as low cost as possible, the price of the component was one of the most important factors to consider in selecting a camera but another major factor is that this camera was used to confirm deployment of the antenna on Mars Cube One, a NASA CubeSat to test the maximum range of CubeSats in space, thus it has space flight heritage [17]. Weighing only 20 grams, the Caspa VL takes up less than 2% of the 1U CubeSat. To process the image and verify if the image taken contains the Hawaiian Island chain Ke Ao uses the Intel Neural Compute Stick 2 (NCS2) with the Movidius chip running machine learning algorithms to do feature identification. The outer aluminum casing of the NCS2 was removed in order to fit it onto the payload board. The NCS2 produces a significant amount of heat and the heatsink is mounted on the PCB board with conductive traces to extract the heat to the rails.

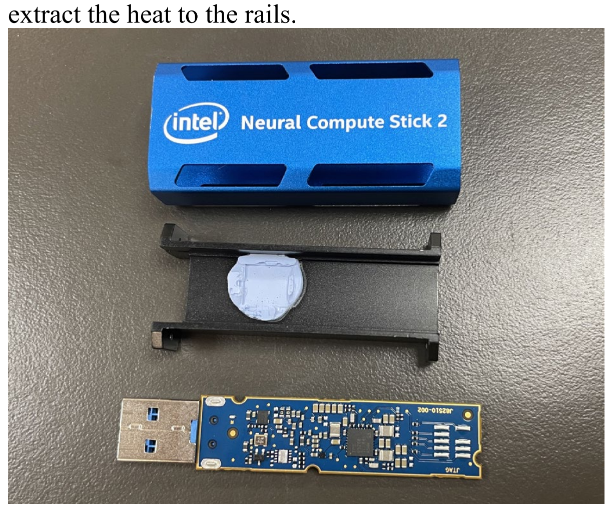

Figure 20: Disassembled Intel stick

Given the specifications of the lens included, and the assumption that Ke Ao will maintain a 400-kilometer orbit, the Caspa VL can achieve about 1200 meters of ground sampling resolution. The pictures produced by the Ke Ao camera are intended to have a positive social impact in Hawaii, aiming to promote aerospace interest and research with a picture of the islands from space built by students in Hawaii.

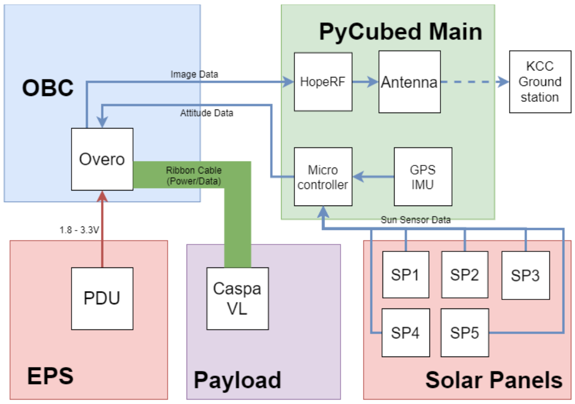

Figure 21: Ke Ao Payload Subsystem Block Diagram

The control logic for the payload is seen in Figure 21 above. The OBC will monitor the attitude vector continuously and will activate the camera when the satellite is in the correct attitude and position for taking a picture.

Flight Software

The flight, ground, and mission operations software are implemented using the HSFL COSMOS Software Framework (http://cosmos-project.org) [18, 19]. COSMOS uses Software Agents to break down the logical processes. **Executive Agent** gathers State of Health (SOH) information from all other Agents, manages a time and SOH driven queue of Native OS commands, and logs both executed commands and SOH. **File Transfer Agent** manages the upload and download of files when there is a ground station contact. This process is modeled after such protocols as the Saratoga File System and CCSDS File Delivery Protocol to be robust over intermittent connections. Files are selectively transferred to and from a set of standard Agent specific directories based on size and priority. **EPS Agent** controls power switches and reports power telemetry. **ADCS Agent** commands the ADCS unit and reports attitude telemetry. **Agent Radio** manages the transmission and reception of radio packets through the RFM98 radio.

Graphical Interface. COSMOS Web is a NodeJS based web framework developed as a mission operations tool for the flight and ground station agents. The web interface utilizes the COSMOS agents generalized functionality to display real-time telemetry data and launch agent requests. COSMOSWeb is capable of live agent telemetry visualization, as shown in Figure 22, as well as historical data queries from the Mongo Database. The user interface is developed with modularity to be compatible with any COSMOS agents. It is built up from customizable widgets, each with a single function. The modularity and customizability of the interface allow COSMOS Web to be tailored to a particular mission without the need for a redesign of the software.

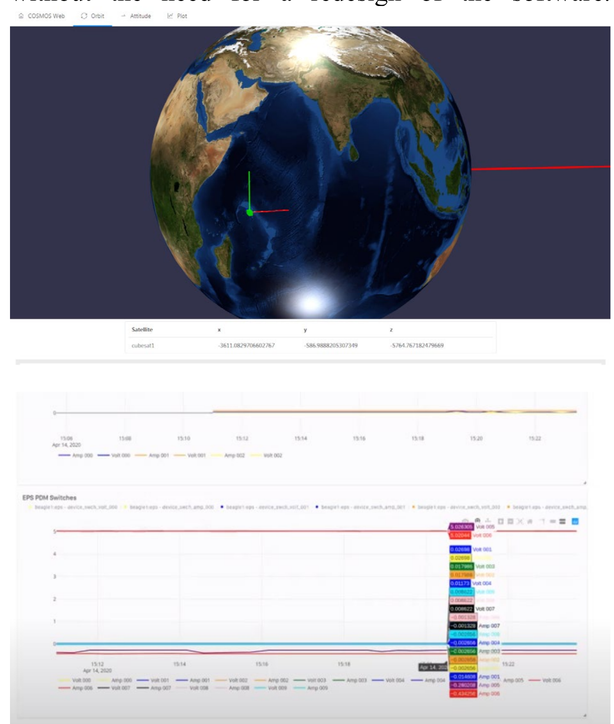

Figure 22: COSMOSWeb view of a satellite orbit simulation

SUMMARY

The Ke Ao mission is a low cost 1U CubeSat developed by undergrad students at UHM to capture images of the Hawaiian Islands and expand on Machine Learning topics. Ke Ao introduces undergraduate students to state of the art Aerospace Engineering topics and technologies such as flight computers and software, orbital mechanics, space to ground radio communications, etc. Ke Ao is expected to be launched in the Fall of 2022 pending acceptance to launch opportunities. The Ke Ao CubeSat development has included undergrad students from all levels in coordination with professional engineers from HSFL in the continuing tradition of providing training to the next generation of space engineers and scientists and will continue to do so during all mission phases.

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