Cal Poly CubeSat Kit – A Technical Introduction to Mk I

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ABSTRACT

The California Polytechnic State University's Aerospace Engineering Department is developing a CubeSat Kit for educational, professional training, and capacity building purposes. The development of the CubeSat Kit follows phases and since its initiation in Fall 2019, eleven undergraduate students and three graduate students have been involved in the initiative. The first phase, CubeSat Kit Mk I, is planned to be completed by spring 2021. For Mk I, the Kit includes a structure, integrated payload processing module (IPPM), electrical power subsystem (EPS), and a backplane. The Kit's Mk I structure was designed to enable additive and subtractive manufacturing. Hence, a wide range of the CubeSat community is able to manufacture the structure depending on their use case, manufacturing capabilities, and overall availability of resources. The IPPM is the interface between the CubeSat bus and payloads. The functions of the IPPM are to autonomously manage and operate all the payloads mounted on the CubeSat Kit, such as CMOS camera and thermal sensors. The EPS is based on direct-energy transfer, includes 5V and 3.3V voltage regulation, and implements lithium-ion battery pack. The IPPM and EPS boards are integrated on the CubeSat Kit using the backplane concept. In parallel to the structure, IPPM, EPS, and backplane, flight software is being developed to be integrated on the Kit's on-board computer for Mk II. Upon completion, the flight software will enable the tasks management of the various elements of the CubeSat Kit. This paper details the design, performances, and verification of the Cal Poly CubeSat Kit Mk I and introduces the design plan for the CubeSat Kit Mk II.

INTRODUCTION

Cal Poly and CubeSats Impact

In collaboration with Stanford University, California Polytechnic State University (Cal Poly) pioneered the development of CubeSats with the establishment of the CubeSat Design Specification (CDS), the de facto standard for CubeSats development[1]. Cal Poly also developed the first flight-proven CubeSat dispenser and over its 20-year of experience, Cal Poly supported the development, launch integration, and/or operations of close to 200 CubeSats from around the world.

The concept of CubeSats, plainly a satellite with a defined form factor that would enable it to fit within a box for safe launch, was developed to democratize access to space. By maximizing the use of space that was unused on launch vehicles while providing a safe way to integrate CubeSats to a launch vehicle using dispensers, barriers to access space, such as cost, were lowered, which enabled a larger number of people, organizations, and countries to access and use space. As a case in point, prior to the first publication of the CDS in 2004, 23 countries owned a satellite. From January 2004 to the end of December 2020, that number jumped to 71. Out of those 71 countries owning a satellite, a CubeSat was the first satellite owned by 20 countries, which represent 42% of the new countries owning a satellite since 2004[2].

Challenges of University-based CubeSat Programs

University-based CubeSat programs present challenges that some are common with the aerospace industry and some are particular to the nature of an educational organization. Those challenges are not only observed at Cal Poly, but also at other educational organizations starting or trying to sustain a CubeSat program[3]:

- Knowledge transfer;
- Variety of duties;
- Feeling of ownership; and
- Documentation.

Universities are rhythmed by the graduation of students. This can create hurdles when students graduate and a CubeSat mission they have been working on is not yet complete. Ideally, a CubeSat mission development will match with the graduation pace and students would have their work tied to senior projects for undergraduates or master or PhD thesis for graduate students. Having the work tied to senior projects, master or PhD thesis enables the work to be recorded and facilitates knowledge transfer so that lessons learned from a project can be implemented onto the next project. In practice, it is not that straightforward and students can leave between quarters or semesters to pursue other extra-curricular activities. This can leave a team struggling to find new members to join and be trained to be brought up to speed on a given CubeSat mission. This lead to the challenge linked to the variety of duties.

Students in a CubeSat program cannot solely focus on the development of the CubeSat mission. They have courses to focus on, and pass. Moreover, a number of students have to work to support themselves throughout their education and be able to pay their tuition fees. Ideally, the core students involved in a CubeSat mission would receive salary for their work. This would secure their time, minimize the number of duties students have to focus on, and overall reduce their stress. This can be difficult to achieve for non-PhD granting universities, such as Cal Poly. In non-PhD universities, it is not only students who have to balance a variety of duties, but faculty do too as their main responsibility is teaching. In non-PhD granting universities, time in a classroom can take up more than 50% of a faculty's work time. This, combined with other duties related to teaching such as course preparation, grading, and students advising, leaves little time outside of weekends to be able to write competitive research grants. Therefore, students and faculty can be stretched in multiple directions making it a hurdle to sustain a CubeSat program without proper support from the institution for the students and the faculty involved.

Sustaining a CubeSat program is important because CubeSats, and spacecraft in general, are multidisciplinary in nature. Their successful development implies a team with varied engineering and non-engineering skills. Moreover, for CubeSat to be launched, they need to be proven safe to be integrated on a launch vehicle. In addition to regulations related to launch safety, other regulations related to communication, orbital debris, and Earth remote sensing data acquisition have to be complied with. A CubeSat project is therefore a system of systems and its completion will take more than a year for most university-based programs. Such a lengthy project, especially combined with the variety of duties, makes it difficult to maintain a team's motivation throughout the inherent setbacks and team members can show a lack of feeling of ownership. Having a launch date can support the team's morale, but is not always sufficient. In years-long CubeSat projects, team building is critical to emulate a togetherness feeling between team members. To facilitate this team building, a project can be divided into small periods of time each marked by a milestone. Those milestones can be design reviews, such as defined in the NASA Systems Engineering Handbook[4], or others as pertinent to a considered project. Then, it is important to celebrate the big and small successes that the CubeSat team goes through, whether those successes are directly related to the CubeSat project or not.

One of the most overlooked aspects of university-based CubeSat programs is documentation. Documentation is an integral part of having good engineering practices. Without the planning of how it is planned to design, manufacture, test, or operate a CubeSat, time and funds can be wasted by going too hastily into the order of parts that do not fit together, manufacture of printed circuit boards that do not work, and verification methods that do not make sense for how the CubeSat is intended to operate in space. Yet, documentation can be daunting if not properly organized and too many software tools are used to develop it. The key to any university-based CubeSat programs, and agile programs in general, is to identify what documentation shall be developed and why. The answer to the what and why can be communicated to the team and contribute to the development of good practices early on in a project, which would have long term benefits not only for the CubeSat mission under development, but also for the future mission as documentation would contribute to the transfer of knowledge between generations of students.

Cal Poly CubeSat Kit, Creating Opportunities from Challenges

The challenges presented in the previous section show that there are many aspects to be taught through the practical development of a CubeSat mission. Not only from an engineering standpoint, but also project management, regulations, and teamwork. As students, and sometimes supporting faculty, joining a CubeSat program do not have practical experience in developing a spacecraft, it can be overwhelming to have to learn, or teach, the various concepts, while ensuring requirements and deadlines are met for the delivery of a CubeSat to be launched and operated on orbit. Moreover, CubeSat missions have evolved into scientific and technology-capable missions[5]; therefore, funding of CubeSat missions has become more competitive and ensuring mission success is critical to sustain a CubeSat program, whose mission would be to launch and operate CubeSats to advance sciences or technologies, for example.

As a non-PhD granting university, Cal Poly's main mission is to educate and train tomorrow's workforce. In particular, Cal Poly's motto is to form day-one ready professionals using hands-on projects. Embracing this philosophy, Cal Poly's Aerospace Engineering Department undertook to develop a CubeSat Kit to be used as a practical platform to demonstrate various principles inside and outside Cal Poly's classrooms.

The Cal Poly CubeSat Kit overall aim is to provide a controlled satellite platform to educate individuals about notions related to a satellite project life cycle. In particular, the CubeSat Kit will:

- Support curricula and professional training development;
- Facilitate access to space for new comers;
- Foster good practices for space engineering; and
- Provide hands-on space engineering experience.

Notions to be taught can be customized depending on whether the end-users are high school students, university students, or professionals from engineering background or not. Upon the completion of Cal Poly CubeSat Kit, various educational areas within and outside engineering can be taught and Table 1 provides an overview of those targeted educational areas.

CUBESAT KIT MK I

Overview

The Cal Poly CubeSat Kit project started in summer 2019. Since its inception, three graduate students and eleven undergraduate students have been involved in its development.

Table 1: Overview of Targeted Educational Areas using the CubeSat Kit as a Practical Application

		Engineering Majors				
		EE	**CPE***	**AERO**	**ME****	**MATE**
CubeSat Flight Segment	**EPS**	- Solar energy conversion - Circuitry for power generation, storage, distribution, and regulation	-	- Power budget - Design drivers for power generation, storage, distribution, and regulation	- Spacecraft configuration	- Coatings - Polymers and ceramics
	STRU	- Spacecraft configuration - Launch environment	-	- Spacecraft configuration - Structural analysis	- Structural analysis - Vibration environment - Shock environment - Statics and dynamics	- Material selection - Material characterization - Structural analysis
	THER	- Analog circuit	-	- Space environment - Thermodynamics - Heat transfer - Orbits	- Thermodynamics - Heat transfer - Thermal analysis - Thermal testing - Thermal management	- Thermodynamics - Heat transfer - Coatings - Polymers and ceramics
	OBC	- Microprocessor/ Microcontroller-based system design - Digital design	- Flight software - Communication protocols - Digital design - Embedded system design - Operating system - Programming	- Mission planning - Mission architecture	-	-
	COM	- RF circuitry - RF verification methods	- Data structure - Communication standard - Programming	- Link budget - Mission planning - Mission architecture - Orbits	- Spacecraft configuration	-
	ADCS	- Electromagnetism	- Programming	- Pointing budget - Control law - Orbits	- Torques and mechanical disturbances	-
CubeSat Flight Segment Interfaces		- Ground segment: definition; mission operations; mission planning; mission architecture - Launch vehicle: integration; launch environment; range safety - Regulations: RF licensing; Earth remote sensing licensing; orbital debris				
Others		- Project management: schedule; budget; multidisciplinary team management - Systems engineering: requirements; work breakdown structure; assembly, integration, and test; risks analysis - Teamwork				

*Here, CPE can also include software engineering and computer science.
**Here, ME can also include industrial manufacturing engineering.

The first version of the kit, CubeSat Kit Mk I, is planned to be completed in early summer 2021 and includes:

- Structure;
- Backplane;
- Electrical power subsystem (EPS);
- Integrated payload processing module (IPPM); and
- Arrays of sensors as possible payloads.

The description of each of the CubeSat Kit Mk I's elements is detailed in the subsequent subsections. The CubeSat Kit Mk I was used as the basis of a program in collaboration with a high school in Cambodia, Liger Leadership Academy (LLA). The program was meant to support the effort of LLA to design, launch, and operate Cambodia's first CubeSat[6].

In parallel to CubeSat Kit Mk I development, the second version of the kit, CubeSat Kit Mk II, was started from fall 2020. In addition to Mk I's elements, Mk II includes:

- Attitude determination subsystem (ADS);
- On-board computer (OBC); and
- Communication subsystem (COM).

Upon its completion, the CubeSat Kit Mk II is planned to be used within Cal Poly classrooms and in partnership with other universities, high schools, and colleges as a hands-on application to teach principles related to space engineering. Upon lessons learned from Mk II's implementation, it is planned to continue to improve the Cal Poly CubeSat Kit. A general timeline summarizing the Cal Poly CubeSat Kit development is presented in Figure 1.

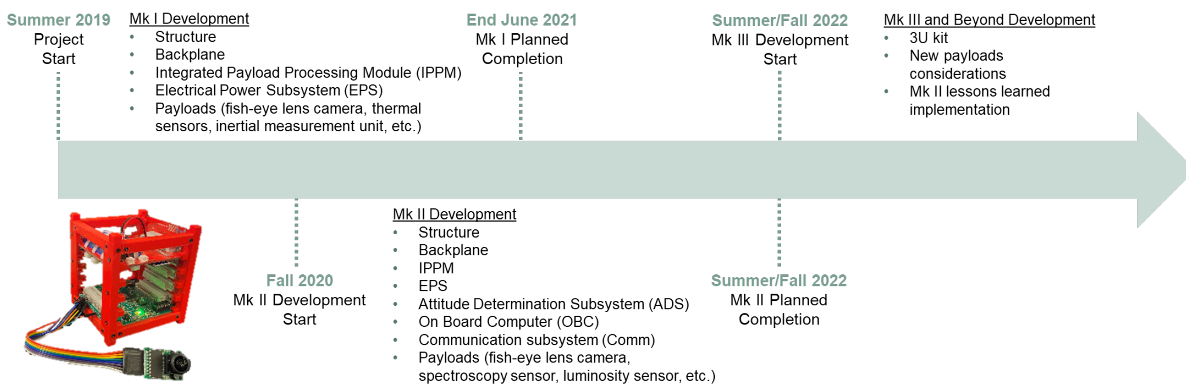


Figure 1: General Timeline of Cal Poly CubeSat Kit Development

Structure[7]

The main design drivers for CubeSat Kit Mk I structure were considerations on:

- Ease of structural elements' assembly/disassembly;
- Capability to be manufactured subtractively and additively; and
- Capability to sustain launch environment.

For the primary structure chassis, monocoque and modular designs were considered. For the internal configuration, PC/104 and backplane/card-slot configurations were considered. Considering ease of structural elements' assembly/disassembly, a modular chassis and use of a backplane/card-slot internal configuration were selected as structural design for the CubeSat Kit Mk I. The illustration of the selected design is presented in Figure 2 and he advantages of the structural design are summarized in Table 2.

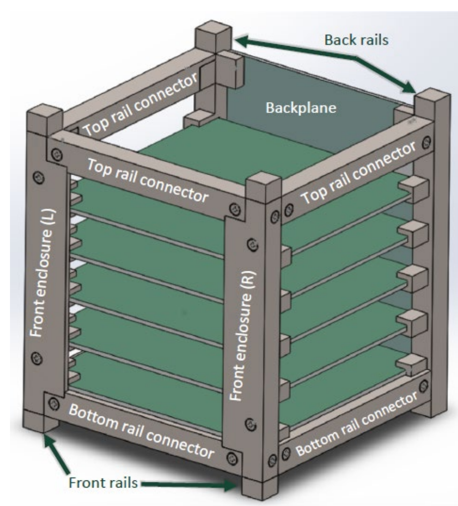


Figure 2: Illustration of CubeSat Kit Mk I Modular and Backplane-based Structure

Table 2: Summary of the Advantages of a Modular Backplane-based Structure

Modular Chassis	Backplane/Card-slot Internal Configuration
- Without side panels, open faces enable to reach out to some components - Number of fasteners to remove to disassemble a board is reduced - Chassis elements can be replaced independently of one another	- Only board of interest has be disassembled when needed - Number of fasteners to secure a board to chassis is reduced

CubeSat developers throughout the world have different resources and needs. For example, as an educational tool, the CubeSat Kit structure does not need to comply with rails surface roughness requirement; whereas if the CubeSat Kit is planned to be launched, it will have to be compliant with the rail surface roughness requirement as described in the CDS[1]. With the variety of needs and resources available to users, it was decided to have one structural design capable of being manufactured with additive or subtractive methods. This further enables to reduce cost associated with manufacturing of a CubeSat structure increasing access to hands-on based space engineering to a larger number of individuals throughout the world.

For CubeSat Kit Mk I, three different materials were considered; two used for additive manufacturing, AlSi10Mg and ABS, and one for subtractive manufacturing, Al6061. Based on those materials, several chassis designs were considered and improved upon based on analytical results. One design was selected as it passed analytical verification and could be manufactured with additive and subtractive methods. For the three cases, the random vibration analysis demonstrated the soundness of the structural design with all analytical displacement being less than 0.5 mm and all margins of safety being positive. The summary of the analytical results and observations is presented in Table 3.

As the three materials were analytically verified, three chassis, one of each material, were manufactured. Chassis using AlSi10Mg and ABS were manufactured using additive manufacturing methods (Figure 3a and b) and the chassis using Al6061 was manufactured using subtractive manufacturing (Figure 3c). Upon manufacture of the three chassis, a 3-axis random vibration test was carried out on each of the chassis. The vibration test enabled to verify and assess:

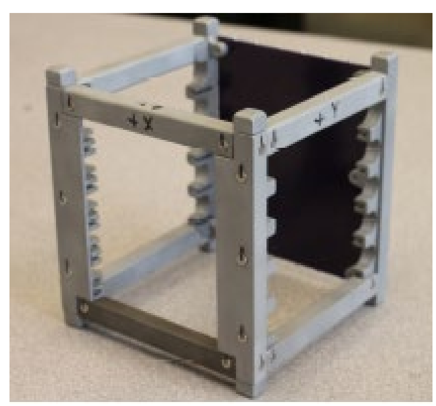
- Workmanship;
- Fundamental frequency; and
- Q-factor.

Workmanship was verified as no fasteners came loose and no parts broke in the three cases. The fundamental frequency could be determined in the three cases; however, the numerical results obtained for the fundamental frequency are inconclusive as coupling with the test dispenser was observed. Finally, the test enabled to experimentally estimate the Q-factor for each case. The experimentally estimated Q-factor was used to refine the numerical analysis, which results are summarized in Table 4 and show that, as expected and observed, the selected design remain structurally sound in each material case.

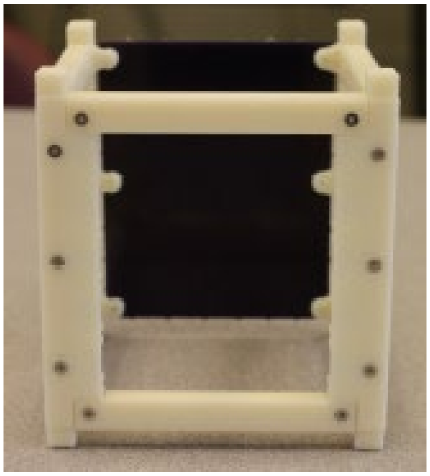
Table 3: Summary of CubeSat Kit Mk I Analytical Results (Pre-Random Vibration Test)

	AlSi10Mg	ABS	Al6061
Displacement Requirement	Less than 0.5 mm		
Assumed Q-Factor [-]	250.00	28.57	62.50
Max. Analytical Displacement [mm]	0.04	0.18	0.02
Average Yield Strength [MPa]	270.00	33.00	276.00
Max. Analytical Stress [MPa]	75.48	10.66	37.50
Margin of Safety [-]	2.58	2.10	6.26
Analytical Observations	As expected: - Stress built up at discontinuities, such as holes and sharp edges - AlSi10Mg has the highest Q-factor, and thus underwent lowest deformation and highest stress - ABS has the lowest Q-factor, and thus underwent highest deformation and lowest stress		

a)



b)



c)

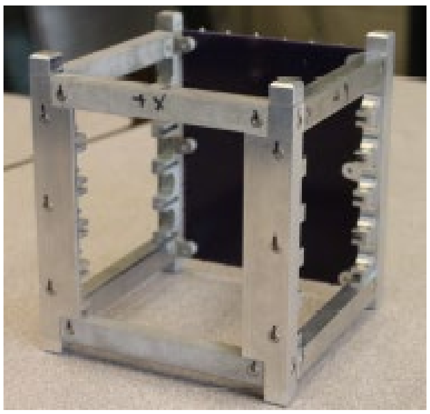


Figure 3: CubeSat Kit Mk I Chassis and Backplane. a) Additively Manufactured, AlSi10Mg; b) Additively Manufactured, ABS; c) Subtractively Manufactured, Al6061

Table 4: Summary of CubeSat Kit Mk I Analytical Results (Post-Random Vibration Test)

	AlSi10Mg	ABS	Al6061
Displacement Requirement	Less than 0.5 mm		
Experimentally Estimated Q-Factor [-]	25.30 (89.88%)*	37.31 (30.59%)*	27.20 (56.48%)*
Max. Analytical Displacement [mm]	0.01 (75.00%)*	0.20 (11.11%)*	0.01 (50.00%)*
Average Yield Strength [MPa]	270.00	33.00	276.00
Max. Analytical Stress [MPa]	23.91 (31.68%)*	12.09 (13.41%)*	24.66 (34.24%)*
Margin of Safety [-]	10.29 (298.84%)*	1.73 (17.62%)*	10.19 (63.78%)*

*Difference between analytical values obtained pre- and post-random vibration test.

Backplane and EPS

As aforementioned, the internal configuration of the CubeSat Kit uses backplane/cardslot configuration. In Mk I, the backplane includes five 48-pin DIN41612 female connectors. This enables up to five different printed circuit boards to be connected simultaneously within the 1U volume of the CubeSat Kit Mk I. One of the connectors is dedicated to EPS (Figure 4).

The EPS board is designed to accommodate direct energy transfer (DET) from the solar panels to the batteries using a steady voltage drop and solar cell protection. The positive terminal of the battery is connected to a shunt resistor that is measured by an INA219, which outputs voltage and current information to the backplane over an I2C bus. The measured battery voltage is available for the rest of the CubeSat Kit as well as 5V and 3.3V power rails, which are regulated by Adafruit's PowerBoost 1000. For energy storage, 18650-sized Li-ion batteries with a 0S3P configuration are implemented. In this configuration, the battery pack is capable of providing 3.7V and capacity of 4,400mAh.

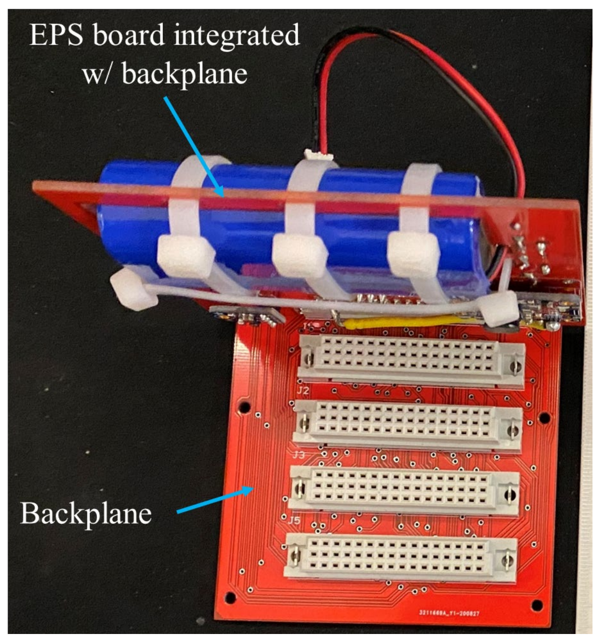


Figure 4: CubeSat Kit Mk I's EPS Board Integrated to the Backplane

After the EPS board was manufactured and assembled, electrical functional testing was carried out. The INA219 sensor was tested using an Arduino UNO, which functioned as expected receiving power over the 5V rail and the 3.3V rail. The DET circuit was tested using Adafruit's 2W solar panel. As the test was carried outside over several hours, DET circuit testing are inconclusive. The DET circuitry seems promising as at the beginning of test, battery voltage was measured to be 4.085V and at the end of test it became 4.100V. However, further verification is required to confirm the soundness of the DET circuitry.

Payloads

Five payloads were considered for the CubeSat Kit:

- Inertial measurement unit (IMU), Adafruit BNO055;
- Luminosity sensor, Adafruit TSL2591;
- Spectroscopy sensor, Sparkfun AS7265x;
- Infrared camera, Sparkfun FLIR Radiometric Lepton Dev Kit 2; and
- Visible camera, OmniVision OV5642.

For Mk I, the focus was put on integrating and verifying the visible camera to support LLA's efforts and the visible camera's integration, operation, and verification is presented in the IPPM subsection.

One of the goals of the CubeSat Kit is to be adaptable to a variety of payloads, i.e., communication protocols, so that an end-user can choose commercially available payloads as useful for their educational goals without having to be constrained on the interface. The only restriction on the choice of the payload on the end-user side will be the power requirement of the payload, which is limited by a 1U capability, about 1.5W. However, it could be argued that there is educational value in choosing a payload that would require more power than what a 1U can provide to illustrate power restriction, duty cycle, battery selection, and other educational notions. Moreover, as an educational tool, payload with power requirement larger than what a 1U can provide could be powered externally using a power supply through the backplane/EPS for example.

***IPPM*[8]**

As CubeSat Kit Mk I does not have an OBC, the IPPM is the board interfacing between the payloads and the user's computer. The IPPM main functions are to manage payloads operations and manage data acquired by the payloads.

The functions of the IPPM are supported by ATSAM3X8E microcontroller with the following features:

- 54 digital input/output pins;
- 12 analog pins;
- 512 kB flash memory;
- ARM processor, 86 MHz; and
- SPI, I2C, UART, and CAN capable.

The IPPM is integrated to the structure through the backplane using a 48-pin male connector, DIN41612, and it implements a 22-pin terminal block to interface with the payloads. For data storage, the IPPM implement MicroSD memory. In particular, there are three MicroSD memory locations, not because that much is needed for data storage, but to enable learning opportunity about fault tolerant circuitry. The IPPM printed circuit board overall layout is presented in Figure 5.

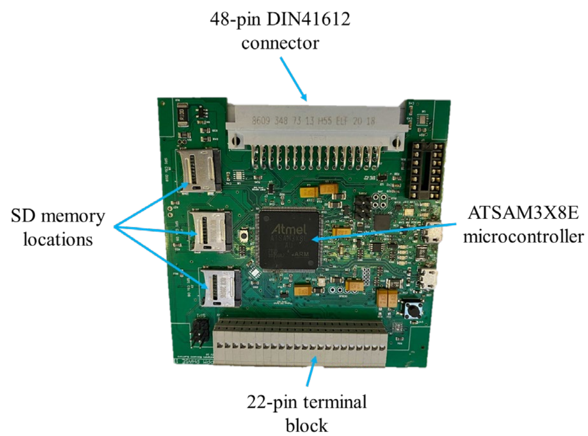


Figure 5: CubeSat Kit Mk I's IPPM overall Layout

The functionalities of the IPPM were verified with an integrated test with the EPS, backplane, and camera module (Figure 6). The test confirmed the IPPM capability to receive command from Arduino IDE to acquire a picture and save it on its memory. An example of a picture acquired during the test is presented in Figure 7 and shows the integrated IPPM, backplane, and EPS through the OV5642 fish eye lens.

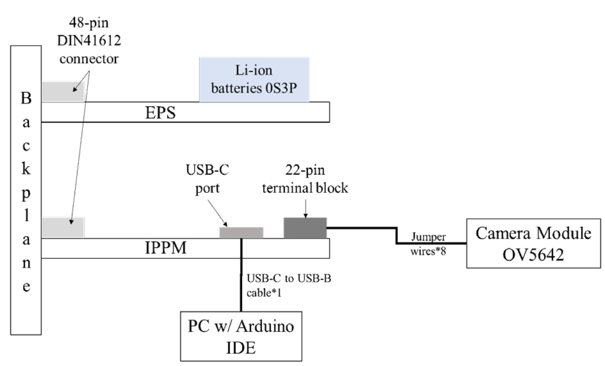


Figure 6: IPPM Integrated Test Diagram

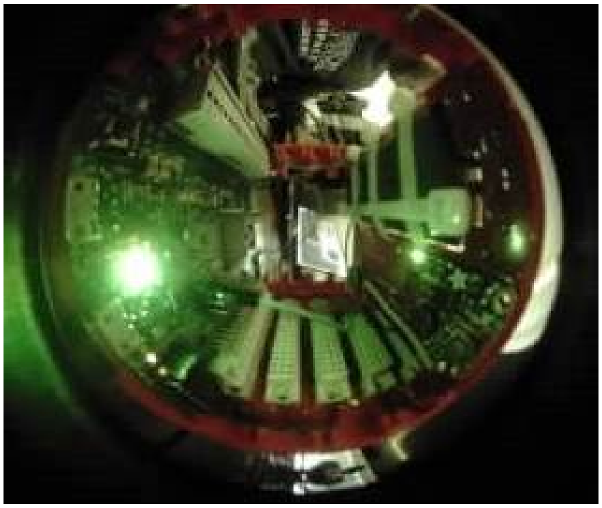


Figure 7: Example of a Picture Acquired during IPPM Integrated Test

CUBESAT KIT MK II

CubeSat Kit Mk II builds on Mk I to include further functionalities such as ADS, OBC, and COM capabilities. One of the main objective of Mk II is to have one subsystem on one board to be allocated to one slot on the backplane. Unlike flight CubeSat that may be constrained on volume available, having one subsystem per board is more suitable for educational purposes to foster a feeling of ownership. This way software-capable, electrical-capable, and other discipline-capable individuals can do focus work together, better understanding the interdisciplinary functions of a considered subsystem; while systems engineers can focus on the interfaces between the different subsystems.

The ADS will implement the IMU that was used as a payload on Mk I and corresponding attitude determination software will be developed. The OBC will take over from some of the IPPM functionalities and will be responsible for the management of the bus subsystems, payloads, and health monitoring. In particular, the flight software is planned to be implemented on a Raspberry Pi computer and its development is based on open source available resources[9]. The development of the flight software will enable practical curriculum development around mission operations and planning. Moreover, basing the development of the flight software on open source will enable a more inclusive dissemination of flight software fundamentals to a more diverse number of individuals. This can help grow the CubeSat community to better support each other in the development of more reliable CubeSat missions. The COM is the subsystem with the most work left to be done for Mk II. It will be based on software defined radio and when develop would enable interface between the CubeSat Kit and its simulated ground segment further enabling the implementation of practical curriculum on mission operations and planning.

SUMMARY

CubeSats can be used as hands-on educational tools to educate individuals on a varied number of technical engineering and non-engineering notions. As students, and sometimes supporting faculty, joining a CubeSat program do not have practical experience in developing a spacecraft, it can be overwhelming to have to learn, or teach, the various concepts, while ensuring requirements and deadlines are met for the delivery of the CubeSat to be launched and operated on orbit. As universities' main mission is to educate, launching a CubeSat is not always necessary. As such, Cal Poly's Aerospace Engineering Department undertook to develop a CubeSat Kit to be used as a practical platform to demonstrate various principles inside and outside Cal Poly's classrooms.

The Cal Poly CubeSat Kit overall aim is to provide a controlled satellite platform to educate individuals about notions related to a satellite project life cycle. In particular, the CubeSat Kit will:

- Support curricula and professional training development;
- Facilitate access to space for new comers;
- Foster good practices for space engineering; and
- Provide hands-on space engineering experience.

The CubeSat Kit is meant to be adaptable to a variety of payloads and end users educational needs. The project started in summer 2019 and since its inception, three graduate students and eleven undergraduate students have been involved in its development.

The first version, CubeSat Kit Mk I, includes: structure, backplane, EPS, IPPM, and an array of sensors as possible payloads. The CubeSat Kit Mk I was manufactured and its main functions verified. The second version, CubeSat Kit Mk II, development started in fall 2020 and will add to Mk I an OBC, COM, and ADS. Upon its completion, the CubeSat Kit Mk II is planned to be used within Cal Poly classrooms and in partnership with other universities, high schools, and colleges as a hands-on application to teach principles related to space engineering. Upon lessons learned from Mk II's implementation, it is planned to continue to improve the Cal Poly CubeSat Kit to fit evolving end-users' needs and constraints.

Acknowledgments

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