Assessment for Completion of CP7

Integration with Revision 6 Avionics

A Senior Project

Presented to the Faculty of

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

Of the Requirements for the

Bachelor of Science in Electrical Engineering

By:

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I began work on CP7 trying to pick up where many amazing people left off, and I wish I had done a better job of following their legacy. I want to thank John Abel and Sean Fitzsimmons for their work on CP7 and their many e-mails helping me to try and move this project forward. I want to thank Jordi Puig-Suari, who helped me with this process and was my advisor. I would also like to thank Brian Tubb, from whom I picked up this project, and who helped me through many times in lab. Thanks to everyone in PolySat and CubeSat for their help and for putting up with my slow pace and many questions. I wish I could have worked on this satellite with a bigger team, or with the original team, but hope that my work here will help CP7 come to fruition, it is an amazing project that many great engineers have put time and effort into, and I hope PolySat can see it to integration.
Abstract

The purpose of this project is the continuation of the CP7 CubeSat project, analysis for integration with new Avionics Systems, and to leave behind instruction for future work for completion of the satellite. CP7 is a satellite in development to support a mechanical and electrical system to experiment on particle damping in micro-gravity. The completion of this satellite needs to be prioritized more than it has been by the PolySat team to honor our work with Northrop Grumman, who have been supportive and helpful throughout the process. This work seeks to aid in the completion of this satellite, so that a launch date can be acquired to further the purpose of PolySat.
# Table of Contents

## Contents

1 Introduction .......................................................................................................................... 1  
   1.1 CubeSat and PolySat..................................................................................................... 1  
   1.2 CP7 Mission.................................................................................................................. 1  
   1.3 Project Motivation ...................................................................................................... 2  
2 CP7 Background ..................................................................................................................... 2  
   2.1 Particle Damping ....................................................................................................... 2  
   2.2 Piezoelectric Actuators .............................................................................................. 3  
   2.3 Mechanical Background ............................................................................................ 4  
   2.4.1 Sensor Board ......................................................................................................... 4  
   2.4.2 High-Voltage Piezoelectric Actuator Driver ........................................................... 5  
   2.4.3 Payload Command and Data Handling Board ....................................................... 6  
3 Analysis for Integration ......................................................................................................... 8  
   3.1 C&DH Compatibility with Current System Board ....................................................... 9  
4 Completion .......................................................................................................................... 11  
   4.1 Mechanical Issues and Remaining Work ................................................................. 11  
   4.2 Electrical Issues and Remaining Work ...................................................................... 12  
   4.3 Software Issues and Remaining Work ..................................................................... 14  
5 Conclusions ........................................................................................................................ 15  
Analysis of Senior Project ...................................................................................................... 16  
References ................................................................................................................................ 19
List of Tables and Figures

Figure 1: Top view Payload Stack.................................................................7

Figure 2: Bottom view Payload Stack..........................................................7

Table 1: I2C Values for C&DH.................................................................10

Figure 3: High Voltage Divider ................................................................13

Table 2: Resistor Values for Voltage Division.............................................13
1 Introduction

1.1 CubeSat and PolySat

Cal Poly's CubeSat program began in 1999 under the name PolySat. A student named Jack Schaffner wrote a paper, winning a contest from Smallsat to begin the PolySat group [2]. With the advisement and leadership of Dr. Jordi Puig-Suari, a cofounder of the CubeSat standard, the team began to develop satellites under the CubeSat standard. In more recent years, the group at Cal Poly has split into CubeSat and PolySat, two collaborative teams working for the same goal of design and launch of CubeSat class satellites. CubeSat functions as the regulator for the CubeSat standard, and designs and improved the P-POD deployment system, with which the CubeSats are mounted onto launch vehicles and sent into orbit. PolySat is the group working with CubeSat here at Cal Poly for the design and completion of the satellite systems that meet the needs of the businesses in collaboration with the PolySat effort. These programs at Cal Poly function as a place for students to learn and experiment in many aspects of the field of engineering.

1.2 CP7 Mission

CP7 is a collaborative effort between Northrop Grumman Aerospace Systems and Cal Poly State University's PolySat program begun in 2008. The PolySat research group at Cal Poly is responsible for design and development of a payload and satellite system meeting the minimum mission requirements as defined by Northrop Grumman.

Minimum requirements of success for CP7 include delivery of a 1U CubeSat with payload instrumentation capable of providing data for the evaluation of a particle damped system in orbit [1]. CP7 must also include avionics system providing support of payload operations including power generation and regulation, and command and data handling supporting a radio link to the ground station at Cal Poly [1]. The payload for CP7 is a particle damper, measuring
the steady state magnitude response of the entire system over a range of 100Hz, with a frequency resolution of 1/8\textsuperscript{th} Hz. The data collected by downlink to a ground station located at the PolySat lab at California Polytechnic State University will be used to conduct analysis on the performance of the particle damper system in a microgravity environment [1].

1.3 Project Motivation

The assessment for integration of CP7 with the new avionics system is necessary in completing the CP7 mission. The payload and corresponding electrical systems of the satellite were designed with the second revision of the avionics used at Cal Poly designed by PolySat students. The current revision of this avionics board is a system designed at PolySat, now obtained through Tyvak Nano-Satellite Systems LLC. The current avionics board is the Tyvak Intrepid System Board, which is the sixth revision of the avionics bus [5]. The board is designed to maximize the capability of the 1U CubeSat platform, and adheres to the CubeSat design specification and P-POD deployment requirements, and is the currently used bus for all of the satellites in development at PolySat. Completion of the CP7 mission, upgrading the electronics to be compatible with the new avionics system is necessary. The goal of this project is to assess the possibility of integration of CP7 with the new avionics system, and provide updated instructions for the new CP7 team to complete the mission.

2 CP7 Background

2.1 Particle Damping

Particle damping originated with a single particle configuration called an impact damper. This configuration consists of a ball bearing within an enclosed cylinder. As vibration in the direction of the cylinder’s axis increases, the force from vibration is dissipated in momentum changes from the ball colliding with each of the ends of the cylinder [3]. This idea is expanded in particle damping in which multiple free moving particles within an enclosed space, and damping
occurs with collisions with walls as well as other particles to produce attenuation of vibration. Particle damping in microgravity is of interest to the aerospace industry due to possible vibrations in a space system in orbit, and the lack of force to dissipate these vibrations. When mechanical noise is induced due to the reduced size of a CubeSat or other small satellite, particle damping may serve as a countermeasure to jitter and vibration in the system [1].

2.2 Piezoelectric Actuators

Piezoelectric actuators are a ceramic material, containing polarized molecules. With electrodes attached to the end of each, an electric potential can be passed through these molecules such that they realign which expands or contracts the ceramic, dependent upon polarity of the potential [8]. An equation describing the mechanical behavior of a piezoelectric actuator is as follows:

\[ F = V \cdot \frac{A \cdot E_b \cdot d_{31}}{4 \cdot t_c \cdot l_c} \]

A is the area of the actuator across, \( E_b \) are the Longitudinal Young's Modules of the actuator, \( d_{31} \) is the transverse piezoelectric charge constant, \( t_c \) is the actuator thickness, \( l_c \) is the length, and \( V \) is the applied voltage [8].

Ceramic piezoelectric actuators are the driving force for the cantilever beams in CP7. A large voltage is applied from the payload's high voltage piezo driver, and the designated piezo causes the cantilever beam to vibrate, allowing the sensor boards housing the accelerometers to collect data on the damping of the beam.
2.3 Mechanical Background

CP7’s original science requirements are to test two different particle damping configurations [1]. The satellite was thus designed with a mechanical system that could be tested for baseline dynamics, and supports three of the base mechanical systems involved, two different configurations of damping and a control un-damped system [7]. The mechanical system is designed to isolate each of the systems, and allow individual vibration of each cantilever beam over a range of frequencies [7]. The mechanical systems in CP7 are three separate cantilever beams, supporting particle dampers of 0%, 95% and 99% particle fill [7], and each of which are driven by a piezoelectric actuator controlled by the electrical payload.

2.4 Electrical Work Completed

CP7 is a project began in 2008 by a team at PolySat in collaboration with Northrop Grumman. John Abel was the team lead for CP7 and in charge of the electrical systems controlling the satellite. Through his work on CP7 the bus for the command and data handling, the high voltage piezo driver board, and the sensor boards were completed. There was a sensor selection, which cumulated with the selection of accelerometers housed on each of the three sensor boards at the ends of the cantilever beams.

2.4.1 Sensor Board

A single sensor board is attached to the end of each of the three beams supported in the system. This allows collection of data close to the tip of the beam, near the site of damping. This also alleviates the need for shielding cable coming from the tip of the beams [1]. The sensor boards will be connected with 30 gauge magnetic wire to the C&DH (command and data handling) board. Each of the boards is shaped in a fashion to allow the use of minimum space. The main purpose of the sensor boards is to provide the greatest signal integrity possible [1].
Each sensor board houses a LIS244ALH accelerometer, chosen for its noise reduction capabilities [1]. The signal captured by these accelerometers is amplified through a TI INA333 instrumentation amplifier, supported by a low noise and precise amplification of incoming signals. The amplified analog signal is fed into two places, a microcontroller on the C&DH board, and an inverting phase shifting circuit which leads to peak detector circuitry. The part passed to the microcontroller is fed into a control algorithm which can be found in Section 5.4.1 of reference 1. The inverted signal is passed to a Schmitt trigger for conversion into a square wave with identical primary frequency to the sinusoidal wave [1]. This is then passed to the C&DH board for further handling. A peak detector is used on the sensor module for capture of the system's output over a cycle of collected data. Calibration of these boards is vital, and has been performed in the past, and will be further discussed in section 3.

2.4.2 High-Voltage Piezoelectric Actuator Driver

The purpose of this board is to provide the necessary electric potential to the desired piezoelectric actuator to drive the cantilever beams at the correct frequencies. This board is capable of measuring its own output to maintain a constant frequency response, and is connected to the C&DH in a stack formation to isolate the difference between the low voltage C&DH board and the high voltage driver board. To create the pure sinusoid necessary for accurate data acquisition this board houses an AD9833 Direct Digital Synthesis chip, allowing very exact resolution of frequencies created [1]. This chip is driven by a crystal oscillator, and the filtered signal is passed to the fine gain stage which delivers amplitudes in response to the frequencies with very fine steps, 256 steps between the low and high voltages for both modes of operation: low and high voltage amplification [3].
The main source of high voltage amplification on the driver board comes from the two EMCO Q-Series high voltage regulators which allow input of 5V to be scaled up to 400V. This is necessary to achieve the difference in voltage of up to 700V required by the actuators to produce desired acceleration. These two regulators create rails of +400V and -400V, producing the desired electric potential. The system can measure its output voltage to allow closed loop control of the amplitude being used, using a voltage divider feeding into a buffer to allow measurement of output signal at lower voltages for easy control.

The driver board is also capable of multiplexing the piezoelectric actuators to determine which to deliver the high voltage supply to. This is controlled by switches connected to an I2C GPIO expander driven by the C&DH board to select the desired actuator to drive.

2.4.3 Payload Command and Data Handling Board

This board houses the heart of the controls of this system, a microcontroller and supporting hardware to store data and communicate with the main avionics system board. In addition to this, the board holds SMA actuator drivers which allow the locking of the beams for isolated vibration, and frequency and phase measurement circuitry [1]. This board stacks with the high-voltage driver board as shown below.
The stack saves space, one of the main limiting factors of the CubeSat specification, thus allowing room for the rest of the system's components. The C&DH board connects to the driver board, the sensor boards, and the system board. The main microcontroller is a PIC18LF8722
programmed using MPLAB. This board controls the I2C interface between the sub-components of the C&DH board, and from the system board. Data from this controller collected from sensor boards is stored in 2 of 4 8-bit EEPROMs which allow writing from the PIC and reading from the system board [1]. This board also has power regulation to allow voltages from 3.2V-5V for the various components housed on the board, and the interconnected pieces. This provides voltage to the sensor boards, and all of the supporting hardware for the microcontroller. The final system on this board is the SMA actuator drivers, in control of selection of which cantilever beam to perform data collection on.

The PIC connects to the system board through I2C lines and GPIO pins. This board’s connectivity to the avionics system is one of the main drivers of this project, and updating this functionality is necessary for the success of the mission.

3 Analysis for Integration

The current C&DH board was developed for use with the revision 2 system board designed at PolySat. Since the design of CP7 the avionics system has evolved, the current version of avionics is the Intrepid System board, which is the sixth revision of the technology. At the time of original design of the C&DH board, the use of PICs was standard at PolySat, and since the improvements to the avionics system and the technology for CubeSats in general, the use of PICs has been almost eliminated. The new Intrepid system board features an onboard ATMEL AT91SAM9G20 processor at 400Mhz [4]. One of the reasons this brings up concerns for the integration of CP7 is that this board has its own I2C lines and handling, as well as GPIO interfacing.
3.1 C&DH Compatibility with Current System Board

The current configuration of the C&DH working with the rest of the system is fairly compatible. Changes to the system board are mostly increases in performance, as well as a slight change in the interfacing to payloads.

Original plans for integration with the system board included designing and ordering a daughterboard for the daughterboard B slot to connect the payload to the avionics. This board was to provide breakout for the C&DH to connect to the system board through the JP4 connector on the C&DH. It was also to support battery monitors, similar to those used on another satellite. The new avionics board supports power monitoring, meaning additional hardware to support this functionality is no longer needed. The connections to the System board, however, have changed and are in need of a breakout board or possibly a recreation of the low-voltage C&DH board with an appropriate connector. The new system board has changed its pin-out since the original revision meant to interface with CP7.

The interface to the system-board can be fixed by a breakout board as previously thought, this board would only support ribbon-cable connectors for the payload to avionics interface of the C&DH board, and the new version of the daughterboard B connection to the system board. An alternative is direct connection to the new version of the payload-interface connector of the system board without going through the throughput of daughterboard B. In either case, the connectivity to the system board should present no significant difficulties and the breakout board is a simple solution to this. Another alternative to the breakout board is the redesign of the C&DH to at least have connectors compatible with direct communication to the system board, although this version of solution to the problem is more costly and time consuming.
The main concern that was addressed for integration was not the pin-out, but rather the possible conflicts with the I2C lines used by the system board and the C&DH board. After some research into both, the conclusion is that there are several conflicting addresses between the two systems. The I2C addresses for the EEPROMS on the C&DH board are as shown here:

<table>
<thead>
<tr>
<th>EEPROM</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT24C1024</td>
<td>1010011</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010010</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010111</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010110</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010001</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010000</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010101</td>
</tr>
<tr>
<td>AT24C1024</td>
<td>1010100</td>
</tr>
<tr>
<td>I2C MUX</td>
<td>1110000</td>
</tr>
</tbody>
</table>

TheGPIO uses the address 1110000, and the main PIC uses 0011010. The issue with these addresses are as follows:

1010000, the address for one of the EEPROMS is identical to the address on the ID chip for the new revision of the system board. 1110000 is an address used for the GPIO expander on both the C&DH board as well as the -Z panel, one of the side panels that would be used for full satellite integration. These problems are both easily addressed.

The first address conflict with the EEPROM on the C&DH board can be solved in the software used to configure the C&DH board. The library in question that is looked at is eeprom.h. This library controls the address used for the EEPROM. Only two of the EEPROMS are actually used for systems operations [4], the other two were included by John Abel as foresight for heritage or future improvements [1]. This library allows us to set the address, the address currently in use is 0xA0, which is 10100000, the extra 0 at the end due to the nature of I2C. This is the currently used EEPROM, and changing this address allows the team to
circumvent this specific conflict. The conflict with the GPIO expanders on the C&DH board and -Z panel is solved through hardware. The address of this expander on the -Z panel is created by populating different resistors on the side panel, which allows the team to set the address to another non-conflicting address. An alternative solution to this problem is to use an I2C multiplexer to isolate the payload bus from the other system components. The easiest solution in this instance is the manual population of the GPIO expander’s address to a non-conflicting one. The alternative solution is supportable if a breakout board is the chosen solution to the connectivity to the system board, but is more costly.

4 Completion

4.1 Mechanical Issues and Remaining Work

The mechanical system for CP7 is an impressive set-up designed by the CubeSat team here at Cal Poly. The current system has been through vibration testing, and is compatible with the test pod. The only remaining issues with the structure of this satellite are an issue of weight, and an issue with the SMA switches positioning.

The weight criteria for a CubeSat is a strict one, and overweight payloads need to be that way with good reason. The current structure for CP7 is 100 grams overweight. There are multiple solutions to this problem. The original suggested solution is to pocket the flight and engineering units using drilling. The structure can handle this with ease, extra material shaving and drilling should not be a problem. An alternative method of weight reduction is a change in battery size. The current batteries used in this structure weigh 91.63 grams. Current missions from PolySat have switched to a standard Tenergy battery with internal regulation circuitry that is UL approved. This is the Tenergy 30005-0 Lithium-ion Cell, a unit of which weighs ~50 g. Using two of these batteries as opposed to the single larger battery is a total reduction in mass of
~83.25 g. This effectively would eliminate much of the need for drilling and shaving, making this process easier. Reduction in mass of the structure should take off at least another 20g of mass to err on the safe side, these holes can be made in any of the tiers of the structure as long as they do not compromise structural integrity and hardware interfacing.

Additional mechanical remaining work is limited. Integration of the satellite involves the conformal coating and staking of the flight and engineering unit boards. In addition to this, the SMA actuators require oil for lubrication. Non out gassing lubricant is required here for flight.

4.2 Electrical Issues and Remaining Work
Currently the payload for CP7, other than interfacing with the System board, functions as necessary. There is an issue with low piezo drive voltages related to the divided signal falling under the hysteresis band of the comparator on the C&DH board [1]. Because of this, a test was performed to measure the trip point and normal voltages of U22, the comparator in question. This measurement is also needed for data processing to improve phase measurement accuracy. Using an oscilloscope and multimeter measurements for the trip voltage showed 2.18 V and 2.19 V for engineering and flight C&DH respectively. The normal high voltage for each board showed to be the correct value of 5.00 volts, with a jump at the trip voltage to 5.375V. These measurements should be noted, and everything seems to be as it should for future completion.
Calibration for the high voltage division was also performed, the resistance values for the resistors on the HV piezo driver board involved in this division are as follows:

<table>
<thead>
<tr>
<th>Resistor</th>
<th>Value (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R34</td>
<td>.922 M</td>
</tr>
<tr>
<td>R35</td>
<td>.922 M</td>
</tr>
<tr>
<td>R36</td>
<td>.921 M</td>
</tr>
<tr>
<td>R37</td>
<td>.489 M</td>
</tr>
<tr>
<td>R48</td>
<td>.453 M</td>
</tr>
<tr>
<td>R39</td>
<td>19.99 k</td>
</tr>
</tbody>
</table>

*Table 2: Resistor Values for Voltage Division*
The results of this calibration show that for the flight and engineering board this division will perform as expected.

Additional remaining work electrically is the wiring of the sensor boards to the C&DH boards, as well as the wiring of the battery to the SMAs in the system, this is a simple process and the appropriate wiring places are labeled on the SMAs.

### 4.3 Software Issues and Remaining Work

The software designed by the PolySat software team for this mission is completed so that testing can be performed, but several changes need to be applied before final integration of the satellite. The first issue was addressed earlier in fixing the I2C line addresses for the EEPROMS, this is an easy fix. There are several other issues still to be resolved in software. The first of these is a problem with the software in control of the fine gain step. This can be seen in reference [7], page 34. The gain step does not account for negative values which causes the program to freeze. This is a known software issue brought up by the previous members of CP7 team, and is mentioned here to ensure the addressing of this problem in the future work on this satellite. Another problem with gain control can be found in the cp7-input-amp.h library in the definitions of GAIN_#, another simple fix mentioned here for future CP7 team.

The final issue in software is the integration of the current payload control software with the software developed by Mike Tran for a Datalogger for CP7. This senior project is functional, but integration with the other parts of CP7's software is critical to mission success. This may present problems in the future when integration is attempted, a member of the software team on PolySat is needed for this task.
5 Conclusions

The conclusion of this project is that completion of CP7 is possible, including all issues regarding integration with new avionics systems. Future teams for CP7 need to be comprised of at least one electrical, one software, and one mechanical team member to assess all of the existing issues. Monetarily the satellite still requires the ordering of several parts, batteries and high voltage regulators, which are inexpensive but necessary. Over all completion of the satellite is not far off, with only minimal calibration needed before final testing. Testing on engineering unit once software issues are resolved will lead to the environmental testing needed for completion and integration of a satellite. This is followed by repeated testing on a flight model. For addressing the Mission Readiness Review that will be required before integration and launch of CP7, please see the MRR for IPEX. This presentation was created, in collaboration with Craig Francis, by myself and is a good layout for future teams to use in their MRR presentations. This is an important step that should be begun early once a flight possibility is found.
Analysis of Senior Project

Project Title: Assessment for Completion of CP7

Student's Name: Daniel Jennings

Advisor's Name: Dr. Jordi Puig-Suari

Summary of Functional Requirements:

This project is assessment, and further work towards the completion, of the CP7 satellite began by previous members of the PolySat team. It is created to document work and provide analysis and assistance to the future members to aid in the completion of this satellite. This project lays out requirements for future work and assesses the completed work on the project.

Primary Constraints:

The lack of a proper team and funding were large obstacles in the completion of CP7 during this time period of work on the project. The future of CP7 depends on having several members of the team collaborate as was done previously on this project before taken over by the current lone member of the team, myself. The completion of this project necessitates ordering parts requiring money, as well as work on electrical, software, and mechanical systems.

Aside from the small team, the collection of the work previously done on this project presented some difficulty. In recent years, PolySat created a standardized documentation system, leaving work before this time scattered and often difficult to utilize. Once materials and information were acquired the progress began, however, this process took a considerable amount of time.

Economic:

The economic impact of the completion of this CubeSat rests mainly in the CubeSat community and the PolySat team here at Cal Poly. Direct costs to the team here are calculated below:

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrepid System Boards (2)</td>
<td>4000</td>
</tr>
<tr>
<td>Side Panels (11)</td>
<td>~363</td>
</tr>
<tr>
<td>High Voltage Regulators for Flight Unit</td>
<td>200</td>
</tr>
<tr>
<td>Batteries (4)</td>
<td>120</td>
</tr>
<tr>
<td>Breakout Board</td>
<td>~300</td>
</tr>
<tr>
<td><strong>Total Cost:</strong></td>
<td><strong>~5000</strong></td>
</tr>
</tbody>
</table>

This project is not for the monetary gain by creating the satellite, but exists as a project for the research team of PolySat to learn about the process of satellite development and production. Possible financial benefit rests in the furthering of Cal Poly and PolySat's relationship with ELaNa (The Educational Launch of NanoSatellites) as well as the rest of the CubeSat community worldwide.
One major way in which this project is beneficial financially is related to the main use of the CubeSat standard. CubeSats are used for inexpensively experimentation, completing a satellite for thousands of dollars instead of millions.

Time spent on this project before the time of the current time spanned over 4 years involving many development cycles for electrical, mechanical, and software development. The time spent on this project involved collaboration with past team members, testing, assessment and analysis, and a large amount of gathering resources.

![Gantt chart of Time Spent](chart.png)

**Commercial Manufacturing:**

No plans exist for further creation of CP7 units, the cost for each is very high and for launch only one system is necessary.

**Environmental:**

This system has minimal environmental impact. The main sources of impact environmentally include resources consumed during production, and use of space in orbit. The structure is comprised of metal, as are most of the involved mechanical systems. The Piezoelectric actuators have minimal impact, and only 6 are necessary for testing and launch. The use of space in orbit is not large, the CubeSat standard places the satellite as one of the smallest orbiting systems, and is classified technically as "space debris" in regards to some of the larger systems currently in orbit.

**Manufacturability:**

This system is designed entirely by the PolySat team, thus the main challenge in manufacturing of the system is creating the structure and integrating all of the supported mechanical systems. The electrical manufacturing is taken care of by ordering the System Boards from Tyvak, and other boards are acquired through PCB printing sites.
Sustainability:

Maintaining the system requires precision with many aspects. The wiring of the system is fragile, especially concerning connections to the piezoelectric actuators. The tungsten steel particles filling each of the two filled cantilever beam systems must be kept free of contaminants, and baked out before the filling of the cavities. The system has very low maintenance costs in terms of resources required. Electricity is required for the testing of the system, but the system itself requires no resources for upkeep and continued functionality.

Ethical:

The CubeSat community and the teams involved in providing launch vehicles are very strict about the restrictions required for a CubeSat's approval for launch. Misuse of the system is very difficult, and there are no ethical implications involved in the production and use of the satellite.

Health and Safety

There are very few health or safety issues involved in the use of this system. If the requirements for the design are met, the system will avoid all health or safety hazards.

Social and Political

The completion of this project will mark a good relationship with the original sponsor Northrop Grumman and PolySat. CP7 also will provide PolySat with another example of exemplary work put into orbit, and provide another aspect for the team at Cal Poly to relate with the rest of the CubeSat community on. There is a workshop for the entire CubeSat community hosted by the CubeSat and PolySat team every year, this project's completion will provide a topic for the team associated to present to the conference.

There are few political implications involved in CubeSat. We are proud to be an American institution, and even have an American flag printed on one of our side panels. PolySat is involved with the government through the organizations that it contacts for proper documentation required for meeting specifications. It is also involved in a good mutual relationship with Cal Poly, and this project may serve to further that relationship which provides the research team such an amazing opportunity.

Development

See Bibliography section for a list of references. Skills learned during this project:

- Proper documentation
- Creation of professional presentations
- Effective testing and troubleshooting techniques
- Effective communication with important professional connections
- Better knowledge of the Aerospace industry
- Understanding of technology and process involved in creation of a satellite
References


