

CAL POLY SAN LUIS OBISPO

# Development of a CubeSat Payload to Model Particle Dampening in Space

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## Design and Implementation of Software for CP7

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## **Abstract**

The California Polytechnic State University CubeSat student research & development group, PolySat, is currently in a mature development stage of a single unit CubeSat designated CP7. The CP7 mission implements a scientific payload designed to characterize particle dampers in microgravity conditions. When subjected to vibration, the momentum exchanges and frictional forces of the particles create a damping effect that can be optimized to suit a number of applications over a broad frequency and amplitude range. In space based applications, particle dampers would serve as a robust and simple device to eliminate jitter in optical assemblies and other sensitive instrumentation. This report will include the design and implementation of the payload software for the CP7 satellite.

## Acknowledgements

I was very fortunate to come into PolySat when I did and to get the opportunity to work on a project that has been touched by so many excellent engineers in the organization. To list them all here would border on ridiculous, but they have all been in my heart and mind while working on CP7. I would like to thank Sean Fitzsimmons for the great deal of help he gave me in the development of the CP7 payload in particular with pesky MPLab. A special thank you to John Brown whom spent numerous hours designing and manufacturing the CP7 structure and whom certainly aided in the success of CP7. Another special thank you belongs to Dr. Jordi Puig-Suari for creating the CubeSat standard and creating opportunities for student run programs like CP7. I would also like to thank Dr. Chris Lupo whom has been an excellent and supportive Senior Project Advisor.

There is one very important thank you and acknowledgement that I need to give, but I fear there is no way that I will do it justice. John Abel has put his heart and soul into CP7 for the past two years. He has designed and redesigned the satellite. He is responsible for the design of most of the electronics and a source of immeasurable guidance throughout the past year. I have learned a great deal about what it means to be an engineer from working with him. Thank you for sharing those many seemingly endless hours of debugging with me.

## 1. Introduction

The California Polytechnic State University CubeSat student research & development group, PolySat, is currently in a mature development stage of a single unit CubeSat designated CP7. The CP7 mission implements a scientific payload designed to characterize particle dampers in microgravity conditions. Particle dampers are mechanical damping devices that consist of an enclosed cavity filled with particles. When subjected to vibration, the momentum exchanges and frictional forces of the particles create a damping effect that can be optimized to suit a number of applications over a broad frequency and amplitude range. In space based applications, particle dampers would serve as a robust and simple device to eliminate jitter in optical assemblies and other sensitive instrumentation.

Due to the nonlinear dynamics of particle dampers, and their dependence on orientation with gravity, the development of a model of particle damper behavior in spacecraft cannot be supported entirely by data achieved from ground tests. The CP7 mission provides orbital data, enabling the development and verification of this model.

After testing the original CP7 sensor design on a NASA Zero-G flight it was concluded that the sensor board and bus interface would require a complete redesign (Abel, et al., 2009). The first component of the redesign was switching the beam sensor from magnetic switches to accelerometers. The second was altering the sensor board to allow the measured peak voltage levels from the accelerometer to be cleared. The third was to add a software driven automatic gain control system to maximize the resolution of the measured waveform. The fourth was to add error checking in the form of full waveform sampling and measuring the phase shift.

This project will include the design and implementation of the payload software for the CP7 satellite including its ability to react to commands received from the satellite bus.



## 2. Background

### 2.1. What is a CubeSat?

The CubeSat program was founded in 1999 by Dr. Jordi Puig-Suari of Cal Poly San Luis Obispo and Dr. Robert Twiggs of Stanford University. Their idea was to develop a standard of picosatellite and a deployment mechanism which would enable students and research groups to design, implement, and deploy experimental payloads at a fraction of the cost and risk. The CubeSat standard defines a single unit CubeSat as a 10cm cube with a mass less than or equal to 1.33kg. The CubeSats are deployed from the launch vehicle using a Poly Picosatellite Orbital Deployer (P-POD) which is capable of deploying 3 1-Unit (1U) CubeSats or any variation of units that fills the 3U capacity. (CubeSat Program, 2009)

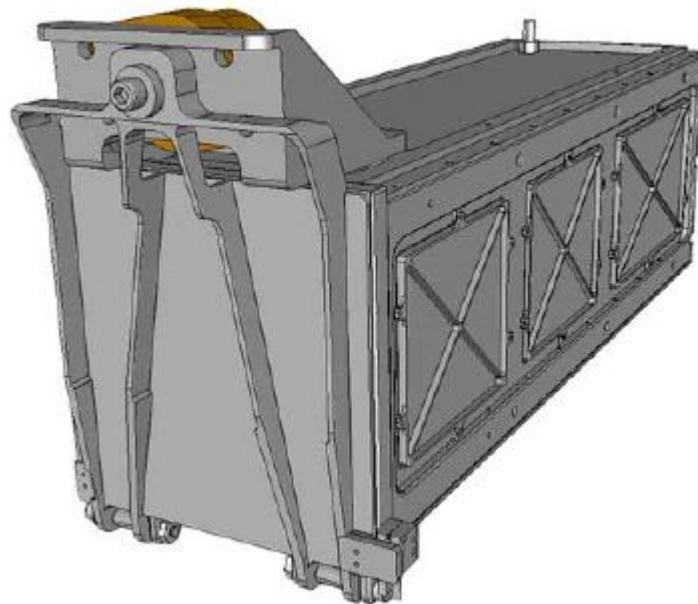
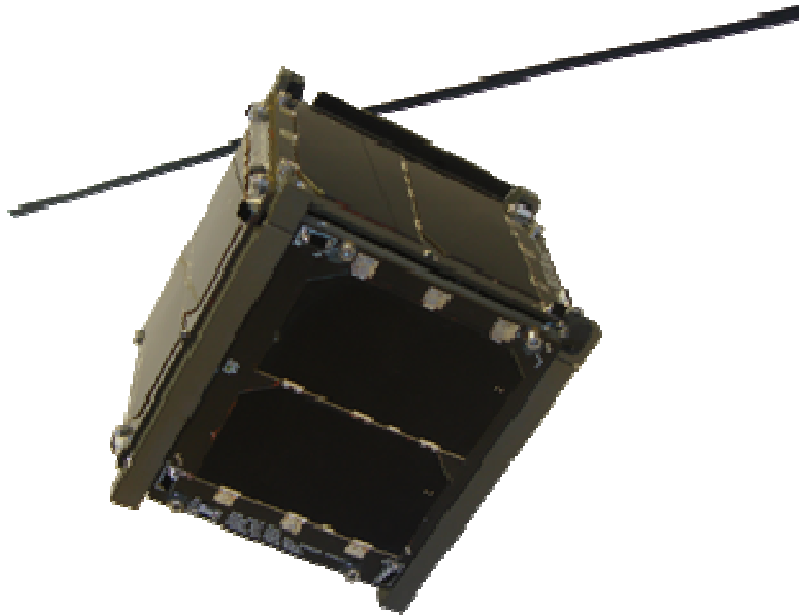


Figure 1: Schematic of a 3U P-POD borrowed with permission from (CubeSat Program, 2009).

PolySat, a California Polytechnic State University CubeSat student research & development group, has been developing CubeSats since its inception in 1999 by Dr. Puig-Suari. PolySat was

founded to prove that CubeSats were a viable platform for orbital experiments and inspire other organizations to join the CubeSat community. PolySat successfully developed three CubeSats: CP3, CP4, and CP6, which are currently in orbit. (Abel, et al., 2009)



**Figure 2: CP3 CubeSat Engineering Model.**

PolySat is currently in development of CP5, the Poly CubeSat Avionics Package (P-CAP), and CP7. The CP5 mission will test a deorbiting technology that utilizes a solar sail to generate drag. P-CAP is being developed in support of The Planetary Society's LightSail-1 CubeSat mission, but will also be used on all future PolySat missions, including CP7, for communication and high level control over the satellite. CP7 will test the affects of microgravity on particle dampeners.

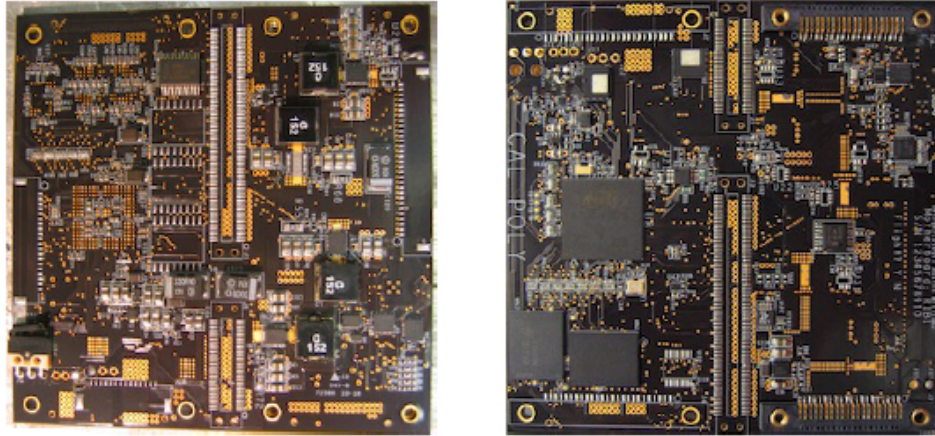


Figure 3: P-CAP Motherboards.

## 2.2. What is Particle Dampening?

Particle dampening is a passive nonlinear mechanical dampening system. Particle dampeners have one or more hollow cavities built into their structure filled with free moving particles. When the structure experiences mechanical vibration from an external source the particles experience exchanges in momentum and dissipate energy through friction that results in a dampening of the input vibration. The structure and fill of particle dampeners can be designed to reduce a spectrum of vibrational frequencies and vibrational amplitudes. Below is a figure demonstrating a simple spring base particle dampener borrowed with permission from Northrop Grumman. (Dr. Stepan S. Simonian, 2008)

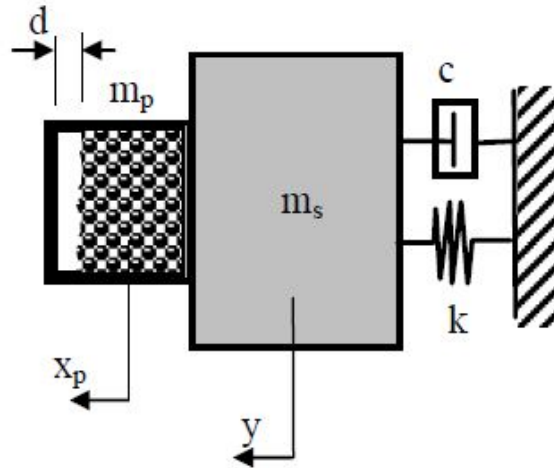


Figure 4: Illustration of a simple particle dampener.

A particle dampener is optimized for an application by designing the mechanical system to have a resonant frequency centered on the interfering frequency. It is important that during the design of the mechanical system that the mass and orientation of the particle fill is taken into account because the distribution of the mass of the system has a direct correlation to the resonance of the system. The underlying problem involved during the design process is particle dampeners are nonlinear with respect to the behavior of the particles and with respect to the systems orientation with gravity. In order to overcome the complexity of the particle dampeners nonlinear behavior models are developed from collected test data of specific particle dampener designs. (Dr. Stepan S. Simonian, 2008)

### 2.3. Why is modeling Particle Dampening in Space important?

Particle dampeners are a cost effective, zero power requirement solution to mechanical vibrations. They are often used in land based applications to affordably overcome unexpected jitter in laser, radio, and photographic structures (Simonian, 2006). The ability to apply particle

dampeners in space based technologies would prove to be less expensive and require less power than existing active dampening solutions. (Dr. Stepan S. Simonian, 2008)

The ability of organizations like Northrop Grumman to implement particle dampening in microgravity is limited by the lack of a modeling data. This modeling data is particularly important due to the nonlinearity of particle dampeners with respect to gravity. It is not evident how a particle dampener will behave in microgravity, but in order to design, implement, and gain heritage it is important to test and model particle dampening in space. (Abel, et al., 2009)

## 2.4. How do CubeSats and Particle Dampening come together?

The CubeSat platform was defined and designed with intention of developing and testing small scientific packages in space in a cost effective and low risk manner. Northrop Grumman saw the benefit in sponsoring the development of a CubeSat standard satellite to test and develop a model of particle dampening in microgravity not only for use in future missions, but also to aid in the educational and technical development of the student engineers involved. Northrop Grumman came into contact with PolySat and the CP7 satellite was born. The CP7 satellite will model of the behavior of three cantilever beam particle dampeners, each with a different percentage fill.



Figure 5: Filled particle dampener cavity of CP7 Test Beam.

## 2.5. What is a Piezoelectric Actuator?

A piezoelectric actuator (or piezoelectric transducer) is constructed of a ceramic material of polarized molecules with electrodes extending from opposing ends. The polarized molecules are arranged such that when an electric potential is applied the molecules will realign themselves expanding or contracting the piezo with respect to polarity and amplitude of the charge. This behavior is known as electrostriction. (Piezotransducers, 2009) A function describing the mechanical force exerted by a piezo is:

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

Where A is the area of the piezo cross section,  $E_b$  are the Longitudinal Young's Modules of the piezo,  $d_{31}$  is the tranverse piezoelectric charge constant,  $t_c$  is the piezo thickness,  $l_c$  is the piezo length, and V is the applied voltage. (A. Oliveira, 2004)

The piezoelectric actuators used on CP7 were provided by Northrup Grumman are Navy Type II PZTA3. Applying the parameters of the Navy Type II PZTA3 it is determined that the piezo will exert .1675lbs force per applied volt to the beam. (Krueger) The piezo is bonded to the beam using nonconductive epoxy. The type of bonding agent used has been found to have a significant effect on the performance of the piezo's ability to transfer energy into the beam. To improve the response of the beam the selection of a more rigid bonding agent is recommended.

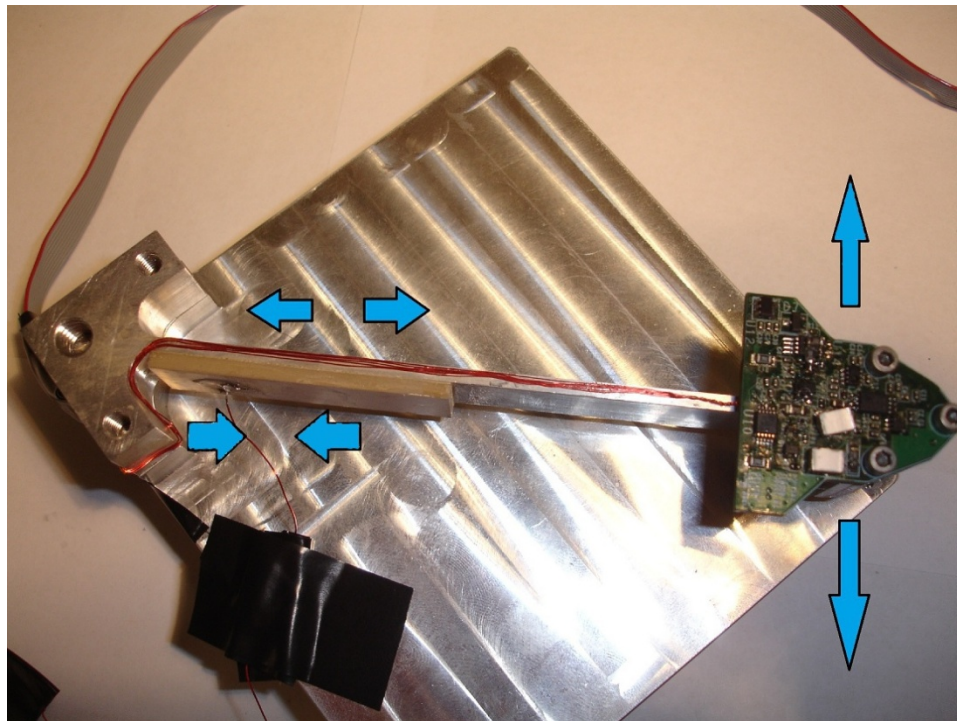


Figure 6: Demonstration of expansion (blue) and contraction (red) of piezo on CP7 Test Beam.

## 2.6. What was learned from the CP7 tests on the NASA Zero-G Flight?

In the Summer of 2009 several members of PolySat were invited to test a proof of concept revision of CP7 on the NASA Zero-G Flight (a reduced gravity parabolic flight). The NASA Zero-G Flight played a significant role in the design of the current revision of CP7. Several issues came to



view during the development process of the proof of concept and from the data gathered during the flight. (Abel, et al., 2009)



Figure 7: PolySat members handling initial CP7 revision during NASA Zero-G Flight.

The first issue that came to light was the use of hall sensors to determine and measure the velocity of the beam tip. This technique utilized magnets and carefully positioned sensors. The largest problem found with this technique was need for the sensors to be carefully calibrated and the tendency of those sensors to shift out of calibration. It became a significant concern that the sensors would not be able to make it through the launch process without moving out of calibration. This technique also had limitations to the degree of resolution. In order to overcome these issues it was decided to utilize an accelerometer appended to the tip of the beam and infer the velocity from the measured acceleration. In order to improve the resolution of the measured beam response it was concluded to implement a stage of automatic gain control to dynamically increase the strength of the signal.



A second issue that came up in the development of the proof of concept was the characteristic decrease in beam response as the input frequency increased. This attenuation was found to be the result of the piezoelectric actuator behaving electrically as a capacitor. By considering the piezo's position in the circuit, the resulting circuit behaves similar to a low pass filter. In order to compensate for the resulting signal attenuation a stage of automatic gain control is implemented. This stage of automatic gain control was also necessary in order to produce a variety of signal amplitudes to fully characterize the particle dampener's performance.

The third issue that came up was determined from the data retrieved from tests run during the flight. The data expressed occasional humps across the frequency spectrum of the test process. It was determined that the cause of these humps was the altering of the frequency over actuating the beam. The over actuation itself cannot be easily overcome; thus, it was concluded to compensate for the presence of this temporary over actuation by implementing a steady state algorithm that waits for the added energy to dissipate.

## 2.7. What is an Accelerometer?

An accelerometer is a device that measures the amount of acceleration experienced. This acceleration is both in the form static acceleration (resulting from gravity) and dynamic acceleration (resulting from a change in velocity). A number of MEMs Accelerometer packages are available on the market today and are found in everything from computer hard drives and cell phones to car engines. Accelerometers can be found in one and two axis versions, but can be combined to determine any number of axial combinations.

CP7 uses two axis 2G/6G configurable MEMs accelerometers attached to the centerline of the particle dampener heads. The accelerator outputs the degree of acceleration in form of a voltage which can be interpreted by an analog to digital converter for further evaluation.

### **3. Description**

#### **3.1. CP7 Overall Design**

The CP7 satellite will test three cantilever beam particle dampeners with 0%, 95%, and 99% particle fills. The data retrieved from testing will enable the development of a model for the development of similar cantilever beam particle dampeners for use in microgravity. Each beam will be activated using a piezoelectric actuator driven by a high voltage board. The response of each beam will be measured using a MEMs accelerometer centered on the head of the particle dampener. Each beam is equipped with a locking mechanism that will enable the beams to be tested individually without interference from the other beams. The control of the piezo driver board, the sensor boards, and the storage of the results will be managed by the payload board. The payload board will communicate with the PCAP via I2C. The PCAP will be responsible for power and communication management of the satellite. All of the above components will be contained within 1U CubeSat.

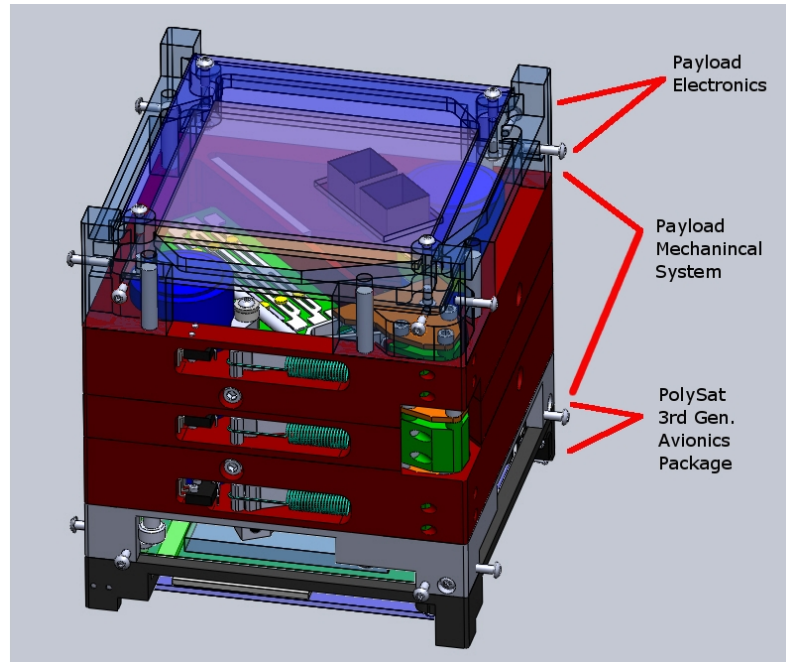


Figure 8: CAD Drawing of CP7.

The payload software will be responsible for managing the piezo driver board, the beam control, the sensor boards, the data storage, and a segment of the communication with the PCAP. The payload software will run on a PIC18F8722 80 pin microcontroller with an effective 5MHz instruction speed. (Microchip, 2008) The payload software will be responsible for meeting the following requirements by controlling hardware through I2C, SPI and GPIOs. The requirements for the payload software are listed below.

## [R-1] Testing

**[R-1.1]** Ability to run identical tests on multiple beams.

**[R-1.2]** Ability to run a series of tests over a range of frequencies.

**[R-1.3]** Ability to set the frequency of a test.

**[R-1.4]** Ability to measure the peak voltage, valley voltage, frequency and phase of the waveform output by the accelerometer.

**[R-1.4.1]** Ability to ensure that the beam has entered a steady state before measurements are taken.

**[R-1.5]** Ability to store the results of tests such that they will not be lost in the case of a power shortage.

**[R-1.6]** Ability to use Automatic Gain Control to maximize the resolution of a test data.

- [R-1.6.1]** Ability to set the gain in steps with accordance to measured values of the peak and valley voltages.
- [R-1.6.2]** Ability to translate measured values after the adjusted gain into equivalent G-force values.
- [R-1.6.3]** Ability for the Automatic Gain Control to utilize both 2G and 6G modes of the accelerometer.
- [R-1.7]** Ability to dynamically adjust the amplitude of the waveform acting on the piezo electric actuator.
- [R-1.8]** Ability to utilize phase and frequency data to validate the results of a test.
- [R-1.9]** Ability to handle bus communication errors with sensor boards.
- [R-1.10]** Ability to store test data for retrieval by the bus.

## **[R-2] Bus Interaction**

- [R-2.1]** Ability to receive a command from the bus.
  - [R-2.1.1]** Command to do a single test.
  - [R-2.1.2]** Command to do a range of tests.
  - [R-2.1.3]** Command to check temperature.
  - [R-2.1.4]** Command to access stored test results.
  - [R-2.1.5]** Command to reset.
  - [R-2.1.6]** Command to enter low power mode.
  - [R-2.1.7]** Command to cancel testing.

The function of the payload can be described as a simple loop. Upon startup of the microcontroller all of the external devices are initialized into their default or standby states. The system then waits for the command flag to be updated signaling that a complete command has been received by the PCAP. The command is executed and the next command will be waited for.

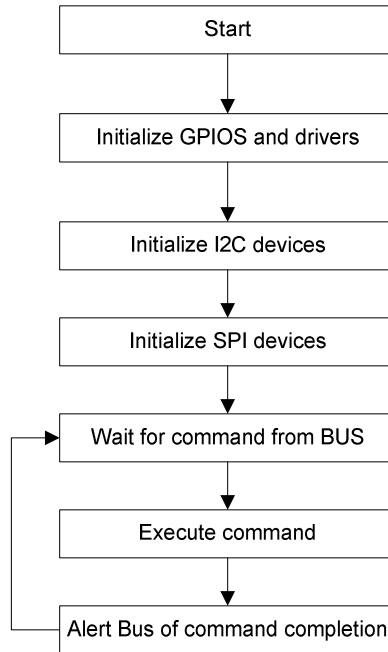


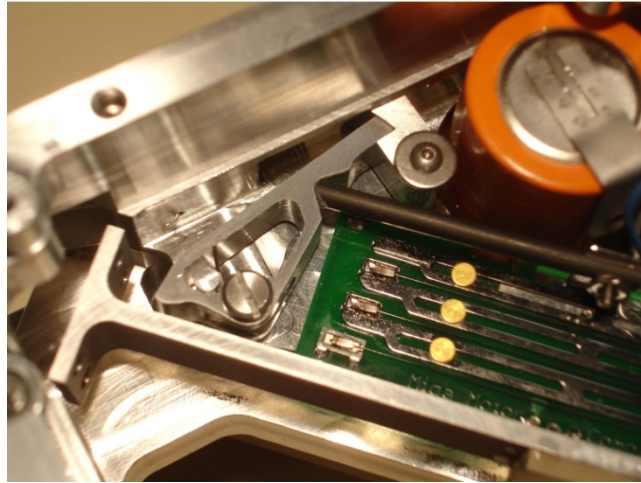
Figure 9: Main loop control flow diagram.

### 3.2. Beam Control

The CP7 Satellite will use three separate test beams. The three beams are designed to behave the same; however, each beam’s cavity will contain a different percentage fill to model how the variation of fill will affect the beam behavior. The first beam is the control beam and will have a 0% fill, the second beam will have a 95% fill, and the third beam will have 99% fill. In order to correctly characterize each beam the other beams must be constrained in order to prevent them from interfering with the experiment. For example, it would be detrimental to the development of the experimental data if the 99% fill beam was dampening the system while running an experiment on the 95% fill.

To resolve the above issues each beam is equipped with a mechanical locking system. The lock is controlled with a Shape Memory Actuator (SMA) that pushes a locking pin into position. A SMA is

also utilized to actuate a release mechanism that unlocks all three beams simultaneously. The SMA is a wire wound between two pulleys and attached to a latch. When a current is applied to the wire it heats up and the wire contracts causing the latch to actuate.



**Figure 10: Green PCB of SMA Actuator connected to black pin of locking mechanism.**

The existing beam lock and unlock algorithms have been found to be oversimplified. The SMA is sensitive to the applied current and generated heat. These inputs to the system are required for functionality; however, if an excess of current is applied or the Shape Memory Wire (SMW) overheats, the SMW can burn out, de-characterize, or even break. Any of these three states would leave the satellite in a non-optimal mode of functionality. If it the wire to burn out is the release actuator, then all of the beams could be stuck in the locked position. If it the wire to burn out is a locking actuator then a beam could be permanently unlocked (always interfering with experimental tests run on the other beams) or permanently locked (no longer able to run an experimental test).

To manage and protect against the SMW from overheating a current sensor and temperature sensor have been built into the system. The temperature sensor can be used to determine the relative temperature of the SMW while the current sensor can be used to estimate the total amount energy dissipated across the wire. The future algorithm will need to evaluate these two conditions

in order to insure that the SMW does not overheat and become damaged during testing or flight. The determination of what amount of energy dissipation and what temperatures are acceptable for the SMW should be determined by developing a model of the system both in atmosphere and in space (heat dissipation and energy requirements to actuate the SWM will be different without the presence of atmosphere). The new algorithm will require the use of timers with interrupts. Delays cannot be used otherwise the estimates of energy dissipation will not be truly accurate.

The existing beamLock algorithm is actually quite simple. It begins by initializing a set of delay values. Delays were determined to be used because it was spec'ed that a rough time limit would be sufficient to protect the SMW from overheating. To reiterate the previous two paragraphs: a rough time limit is not sufficient to protect the SMW from overheating. The beam position line is then checked and determined if it is locked. If it is locked, the SMA Driver is set low and the algorithm quits. Otherwise, the number of BEAM\_LOCK\_TIMER\_CYCLES that have come to pass is evaluated. If the max has been reached and the beam is still not locked an error flag is set, the SMA Driver is set low and the algorithm quits. Otherwise, the SMA Driver is set high and the count is incremented, and the algorithm delays BEAM\_LOCK\_TIMER\_STEP.

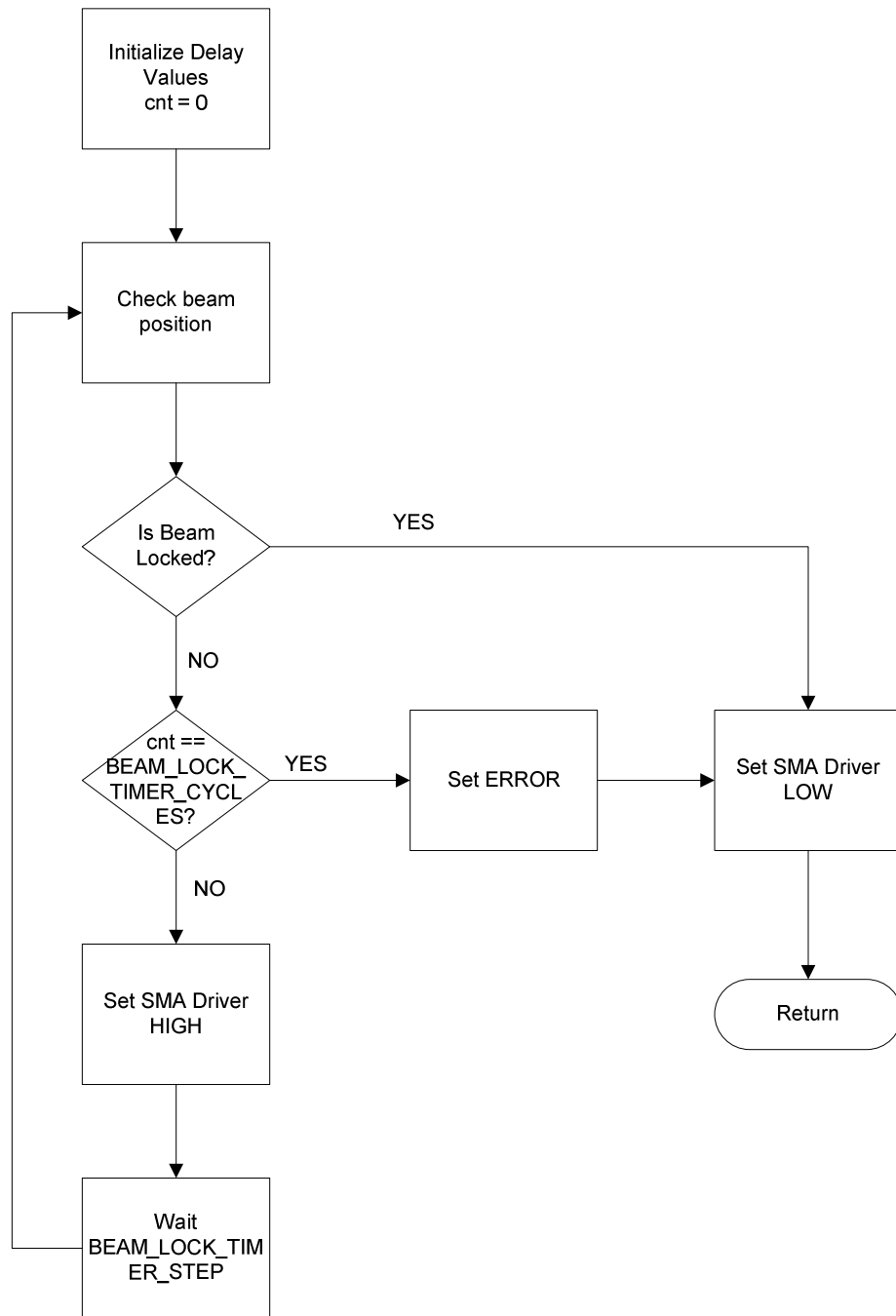


Figure 11: lockBeam algorithm.



The unlockAllBeams algorithm is similar to the lockBeam algorithm. The primary difference is the unlockAllBeams algorithm drives the SMA Release actuator and checks the position of all three beams. The returned error directly corresponds to the beams that did not unlock correctly.

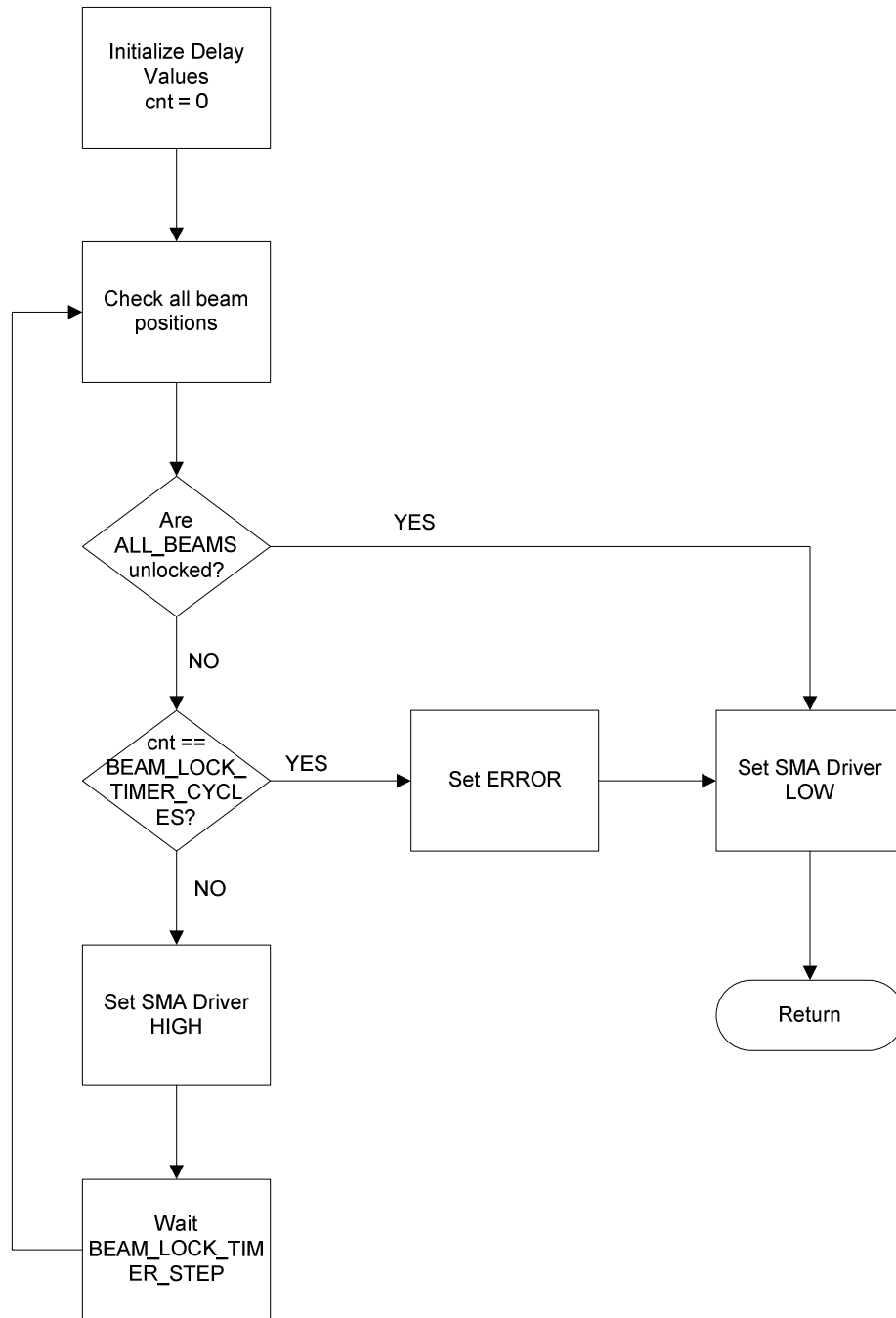


Figure 12: unlockAllBeams algorithm.

The unlockBeam method is designed to leave the system with one beam unlocked. It begins by calling the unlockAllBeams algorithm. It then proceeds to lock the two beams that are not the specified beam to remain unlocked.

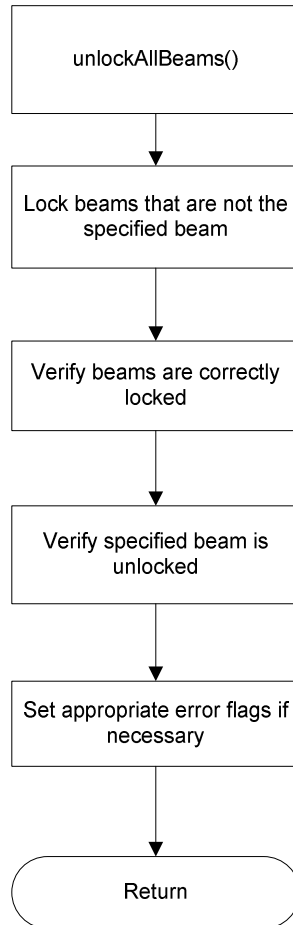


Figure 13: unlockBeam algorithm.

### 3.3. Utilizing Automatic Gain Control on the Sensor Board

After the NASA ZERO-G Flight it was determined that the resolution of the output from the accelerometer (or at the time the hall sensor) needed to be increased. Part of this need for a increased resolution is due to the low voltage output of the accelerometer. The setAGC algorithm is a highly refined automatic gain control that utilizes a table to specify gain steps, stages, and limits. The complexity of the algorithm is increased by the accelerometer being able to measure the acceleration in a 2G range and a 6G range. The complexity of the algorithm is also increased to handle potential noise in the system that could and has caused the gain to be set incorrectly.

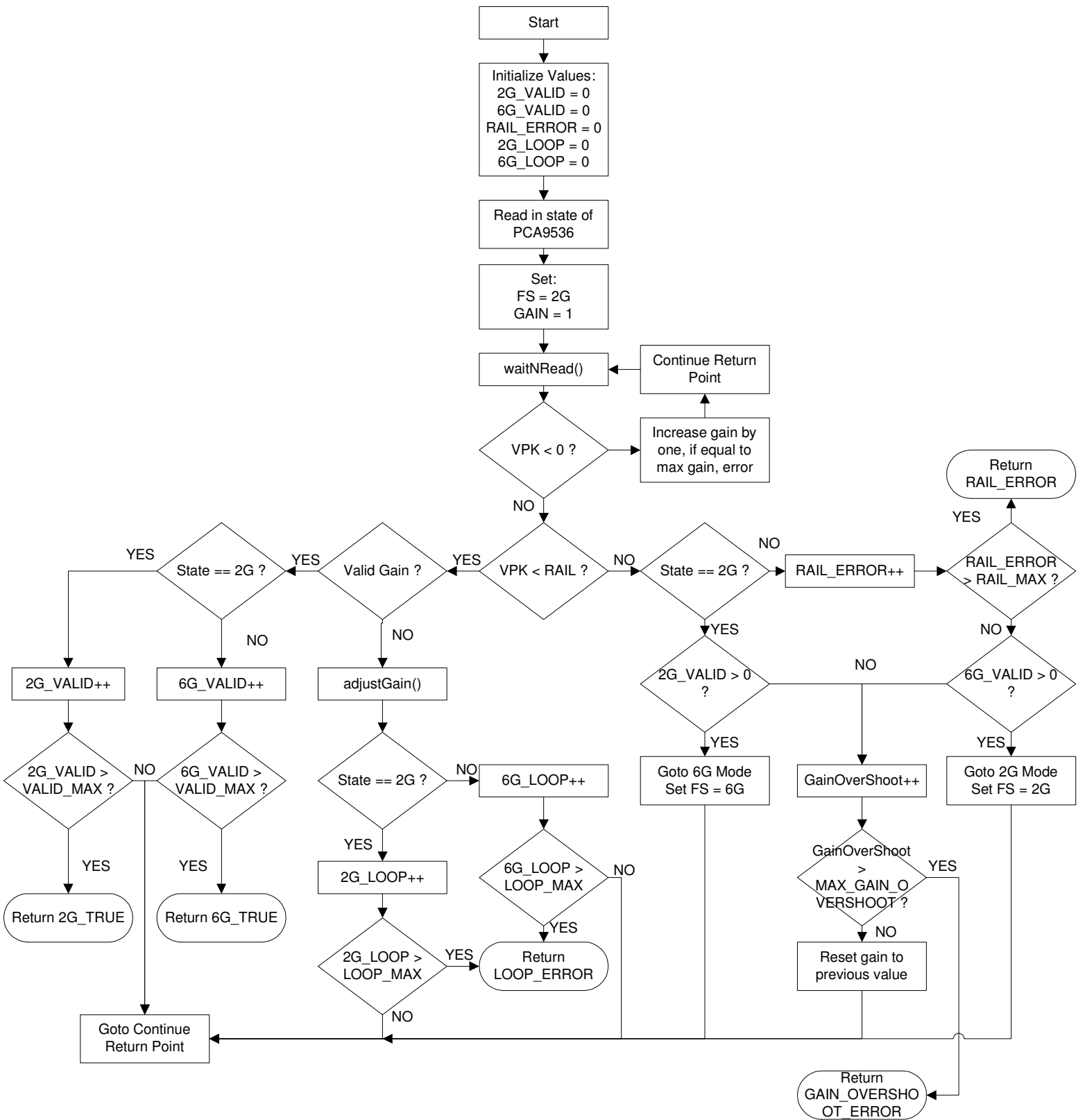


Figure 14: setAGC algorithm.

The adjustGain algorithm is called by setAGC. adjustGain evaluates the current VPK value with respect to the current gain, looks up the appropriate gain setting based on that result in the gain table, and sets the AD5245 with the respective gain setting.

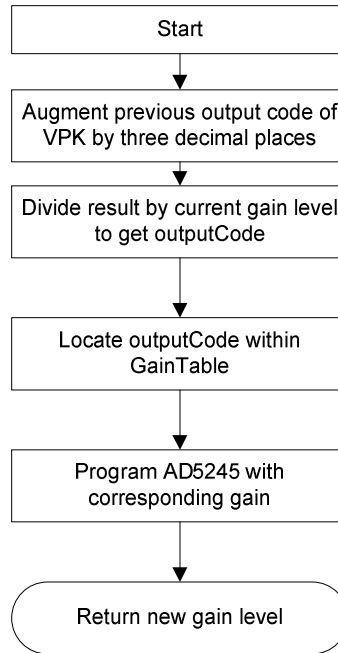


Figure 15: adjustGain algorithm.

The waitNRead algorithm is called by multiple functions to read the current VPK value. waitNRead toggles the RST pin on the PCA9536 which refreshes VPK and eliminates spikes that could be caused during frequency changes which were found during the NASA Zero-G Flight. After the reset the system delays for the equivalent of 1.5 periods of the current waveform to ensure the peak voltage is captured. A conversion in the ADS1115 is then initiated, read, and the result is returned.

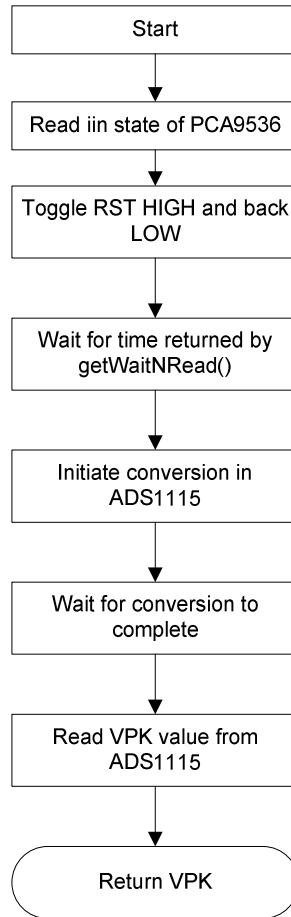


Figure 16: waitNRead algorithm.

The findSteadyState algorithm is essential in determining a valid VPK value and is called after setAGC. The findSteadyState algorithm essentially waits for the mechanical system to enter a stable mode and accounts for the fluctuations in the behavior of the beam that result from adjusting the frequency and amplitude of the waveform manipulating the beam. This equivalent to waiting for the beam to debounce.

The need for the findSteadyState algorithm was determined from data gathered during the NASA Zero-G Flight. A result of transient frequency alterations, a characteristic of the programmable waveform generator, and gain increases the beam can actuate to greater degree than desired. This imperfect deformation of the beam can result in the beam temporarily becoming

more excited than intended and the findSteadyState method waits for this excitation to settle out of the system.

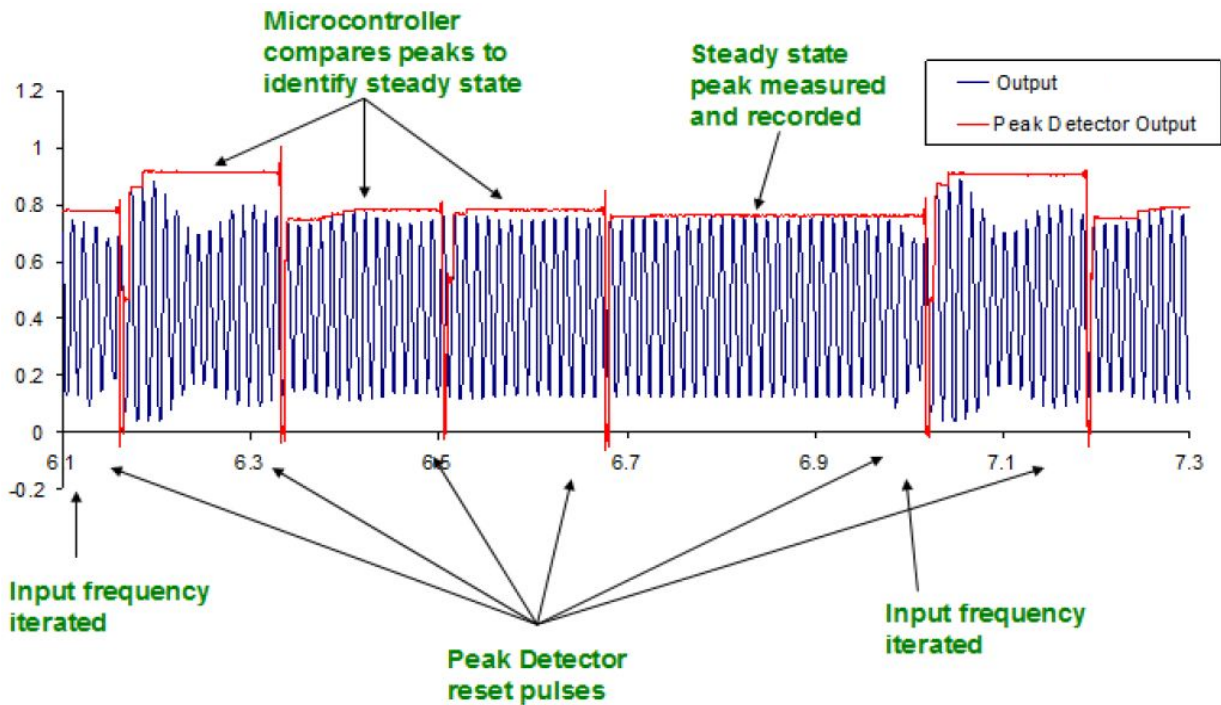


Figure 17: Graph demonstrating need for steady state algorithm.

The findSteadyState algorithm samples the VPK value using waitNRead repeatedly over a period of time. A valid or steady VPK is determined when the difference between the previous VPK and the current VPK is within the Steady State Margin (SSMRGN). If after a SS\_LOOP\_MAX trials fail to find a steady VPK and the SSMRGN is less than SS\_MRGN\_MAX the SSMRGN is increased by SS\_MRGN\_INC. This behavior enables the algorithm to handle small amount of noise on the system (either electrical or mechanical).

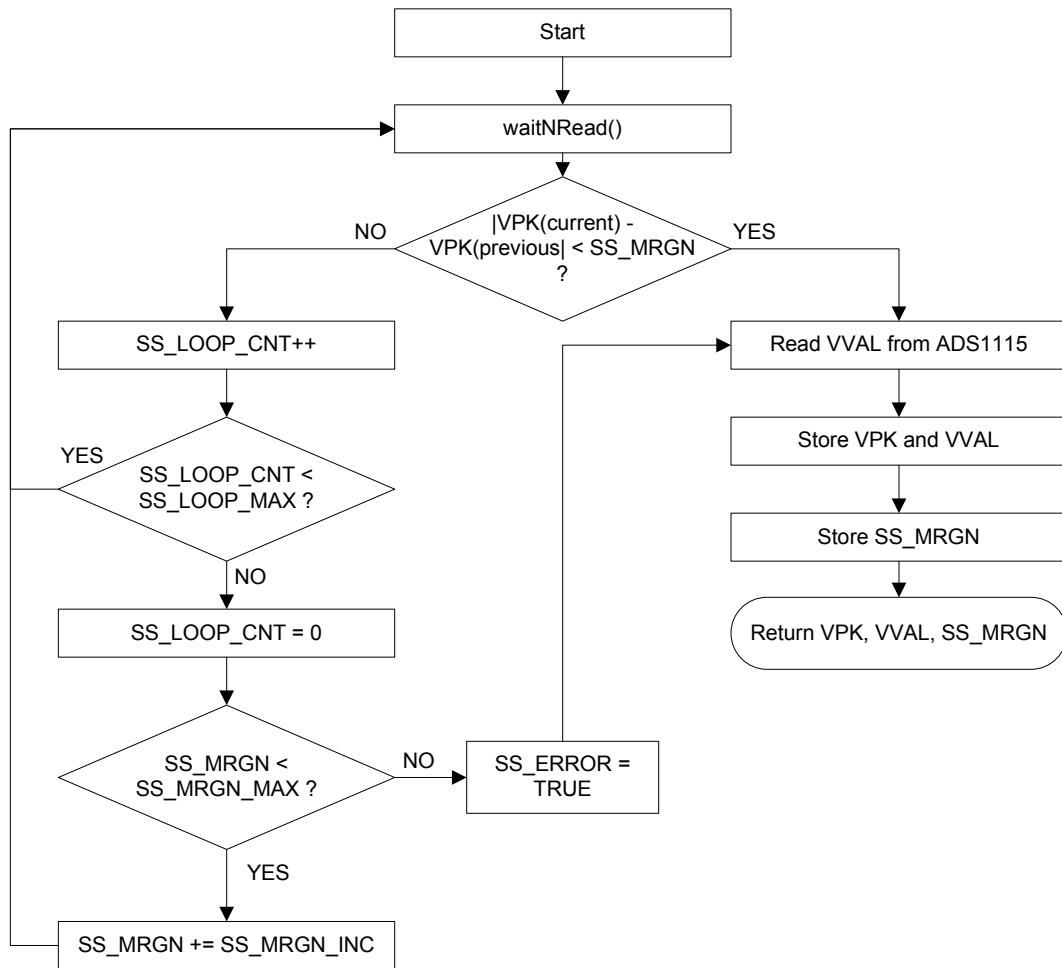


Figure 18: findSteadyState algorithm.

### 3.4. Dynamically adjusting waveform frequency into Piezoelectric Actuator

In order to replicate the behavior of a vibrating structure using the Piezoelectric Actuator and develop an effective model of the PD's behavior it is necessary to be able to generate a waveform in a spectrum of frequencies in discrete steps. This made possible by using a programmable waveform generator which utilizes direct digital synthesis (DDS). The Analog Devices AD9833 DDS IC was selected for this project. The AD9833 can generate square, saw tooth, and sinusoidal waveforms at frequencies from 0-12.5MHz with step sizes as small as 0.004Hz depending on the configuration.



The AD9833 is configured by a required external oscillator. The faster the external oscillator (MCLK) the greater the spectrum of possible frequencies and the larger the step size; while the smaller the MCLK the smaller the spectrum of possible frequencies and the finer the resolution of the step size. Another important characteristic of the AD9833 is that with smaller MCLKs jitter in the output waveform becomes an issue. In other words, it is possible to use a smaller MCLK and achieve a very fine resolution step size, but the resulting jitter, could in certain situations (CP7's), reduce the clarity and accuracy of the experiment. For CP7 a MCLK of 16MHz was selected because it provides an 8MHz low jitter spectrum with 0.06Hz step sizes. It was previously determined that a step size of 0.5Hz would be sufficient in order to produce an effective model of the PD.

The AD9833 is described by its documentation as an "SPI Compatible Device." This was originally interpreted as meaning the AD9833 would function using the SPI Protocol; however, it quickly became clear that this was not the case. It turns out that the AD9833 is "compatible" in the sense that it can utilize the SPI lines for communication while the other SPI devices are not in use. The biggest difference between the protocols is the AD9833 uses 16 bit words separated by one or more clock cycles which are not compatible with the PIC Microcontroller SPI driver which uses 8 bit words separated by one or more clock cycles. In order to resolve this issue it was required that a Bit Bang Driver be written. The code and documentation for this driver can be found in `cp7-spi-ad9833.c` and `cp7-spi-ad9833.h`.

The use of the AD9833 DDS is a significant difference compared to the solution used for the NASA Zero-G Flight. That revision of CP7 utilized a second microcontroller that's sole responsibility was the generation of sinusoids at the desired frequencies. This technique was limited in the number of possible frequencies that could produced, the complexity of adding additional

frequencies, plagued with problems resulting from the single thread operation of the microcontroller, and required more board space than the DDS.

### 3.5. Dynamically adjusting waveform amplitude into Piezoelectric Actuator

The CP7 revision developed for the NASA Zero-G Flight showed that as the Input Frequency increased the reaction of the beam from the signal slowly attenuated. Research performed by John Abel and several others at PolySat found that this attenuation was not the result of mechanical influences, but was the result of the electrical characteristics of the piezo. The piezo has many behavioral characteristics similar to that of a capacitor. By considering the piezo driver circuit [see appendix], the generated waveform is passed through an amplifier, through a resistor, and across the piezo (a capacitor); it becomes clear that overall circuit behaves like a very poorly designed lowpass filter. This problem is overcome by implementing Automatic Gain Control for the piezo driver and as an added bonus it allows multiple amplitude inputs to be used to characterize the particle dampener.

The piezo driver automatic gain control or input amplitude automatic gain control (inAmplAGC) is not as fine grained nor computationally intensive as the automatic gain control for the sensor boards. The premise behind the algorithm is to break the problem into three parts. The first part, setCoarseGain, is intended to overshoot the goal output (VSET) by as little as possible by evaluating four possible coarse gain states. The second part, setFineGain, is intended to take large then small steps through the gain settings to reach an output as close to VSET as possible. The first and second parts are to be used prior to running a frequency sweep of tests or a single test. The third part,

updateInputAmpl, is intended to adjust the gain to compensate for changes in the output as a result of increasing attenuation.

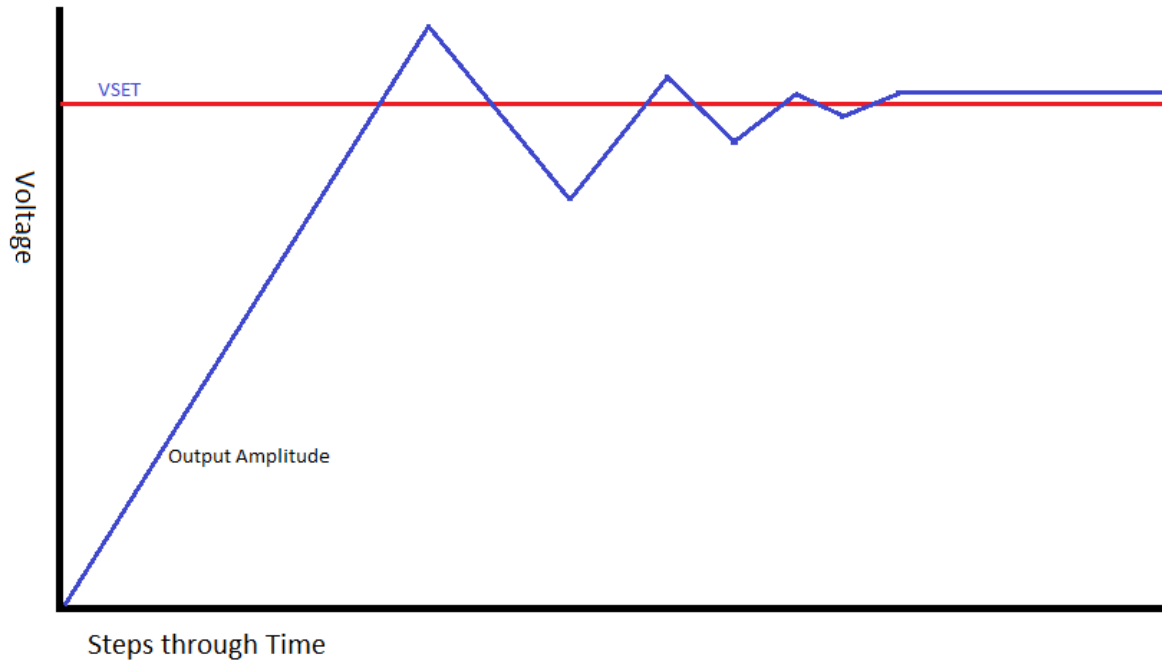


Figure 19: Graphical representation of the setCoarseGain results.

The setCoarseGain algorithm has four possible states. The first state is the Low Voltage Mode (LV\_MODE). When in LV\_MODE the nominal amplitude of the waveform is 2VPP to 86VPP. The remaining three states are not in LV\_MODE and can produce a nominal amplitude of the waveform from 20VPP to VMAX. The remaining three states are gain settings controlled by the ADG621 based on which outputs are selected from the AD5280 from O1 and O2 and provides gains of 8, 25, and 90.9. The exact characteristics of this interaction can be clearly seen in the Piezo Driver Schematic found in the appendix. A flow diagram for the setCoarseGain algorithm can be seen below.

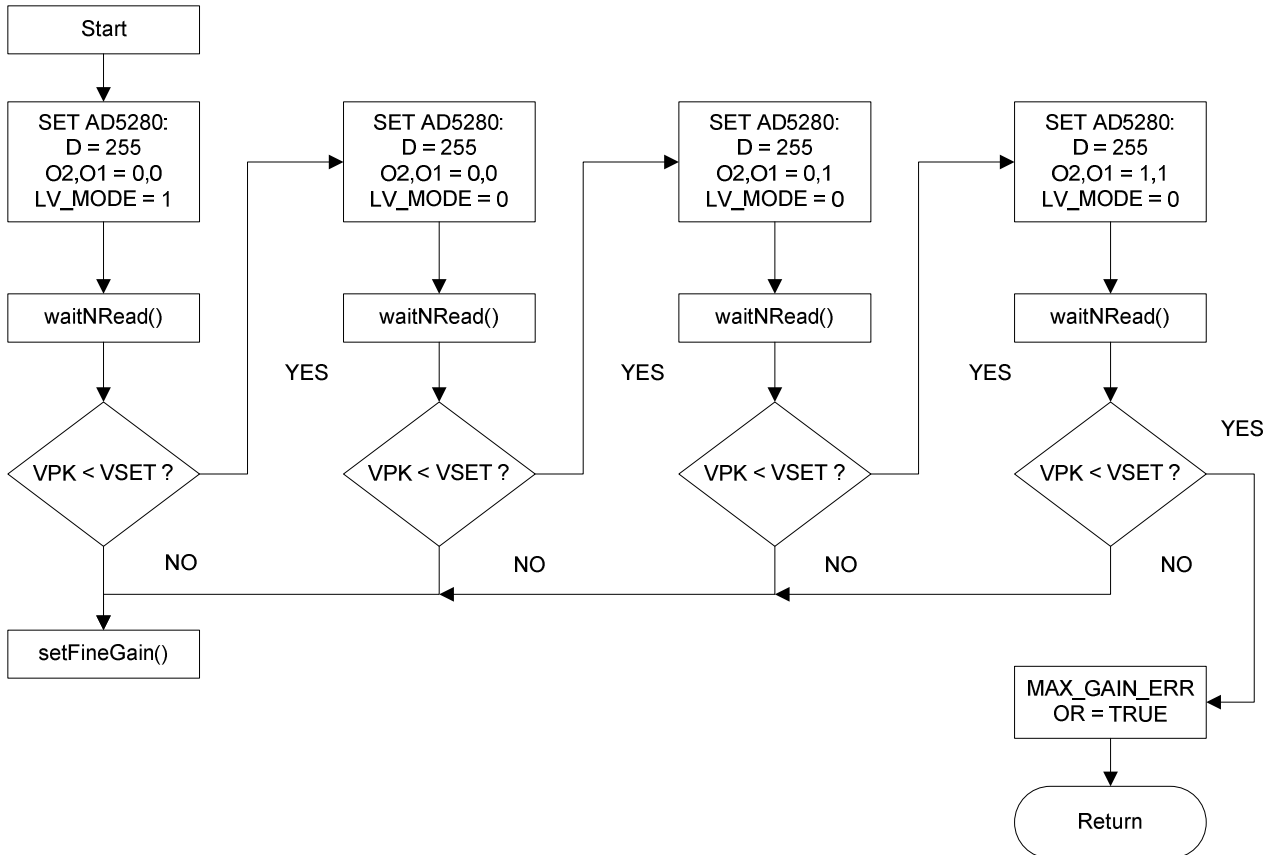


Figure 20: setCoarseGain algorithm.

The setFineGain algorithm is called at the end of the setCoarseGain algorithm. It is responsible for adjusting the gain controlled by the AD5280. The AD5280 is an I2C Digital Potentiometer with 255 equally distributed stages of resistance. The setFineGain circles the output amplitude into VSET. Although it is unlikely the setFineGain will achieve the exact desired VSET it does achieve an amplitude that meets the accuracy requirements of the project.

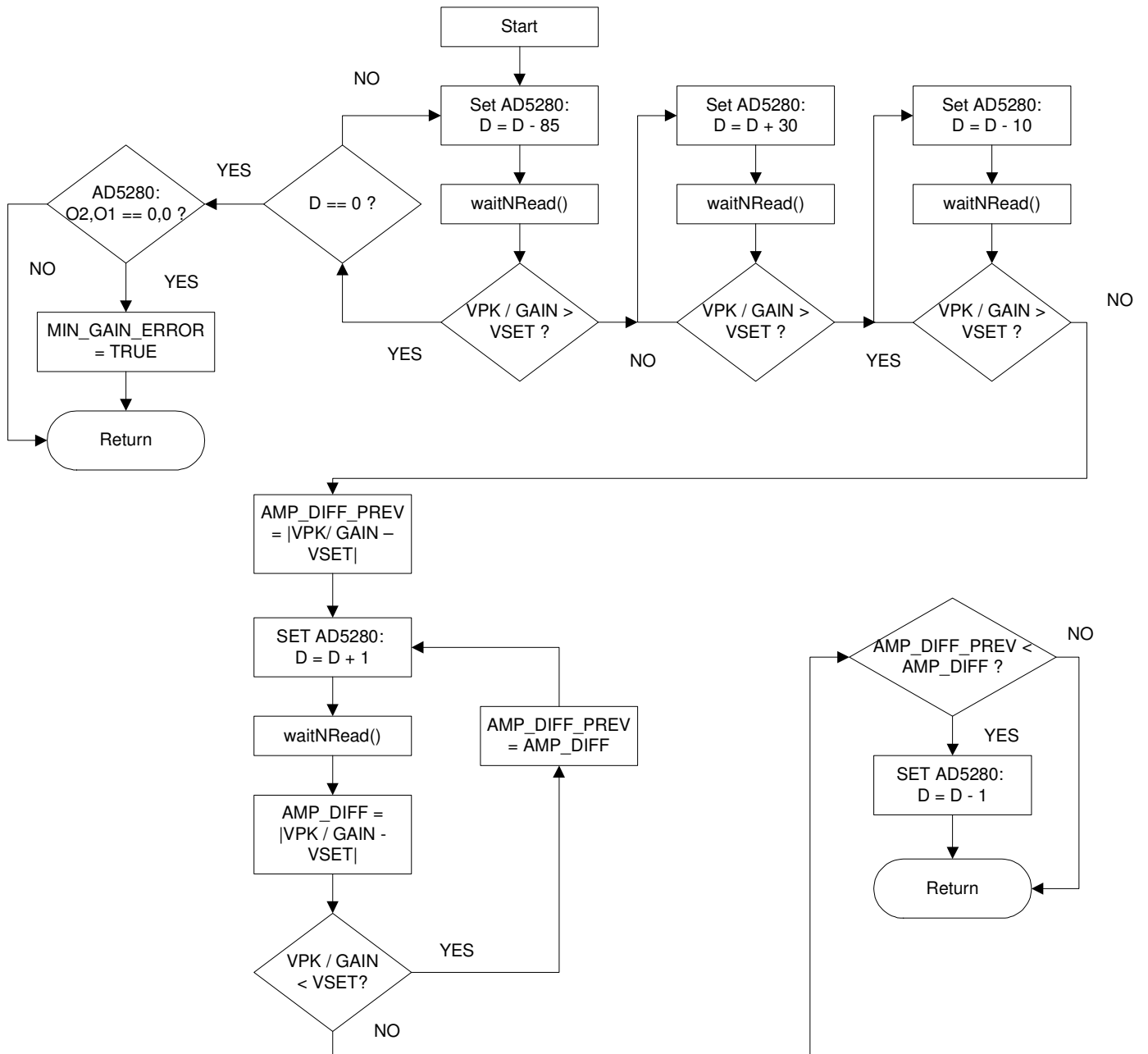


Figure 21: setFineGain algorithm.

The updateInputAmpl algorithm is designed to make minor adjustments to the output amplitude in order to compensate for the attenuation resulting from the increased frequency. The updateInputAmpl algorithm either steps up or steps down the gain until it reaches an output amplitude as close to VSET as possible. It is capable of determining that the desired VSET is out of the range of the current coarse gain setting and will call setCoarseGain to nominalize the coarse and fine gain.

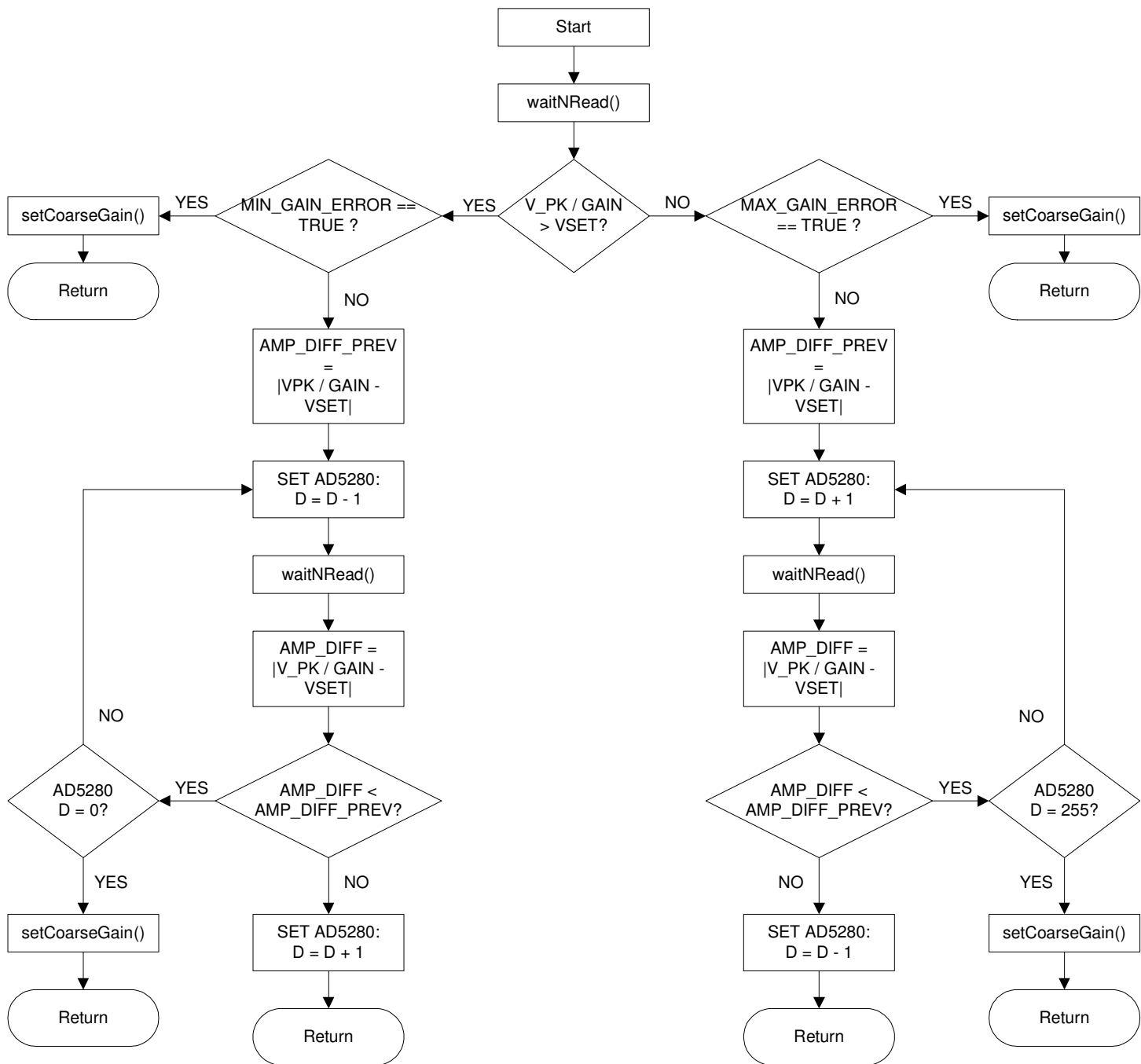


Figure 22: updateInputAmpl algorithm.

### 3.6. Determining phase and frequency of test waveform

The NASA Zero-G Flight raised a concern about how accurately the beam was actuated by the piezo driver board. This was both a concern of the magnitude, but also the frequency the beam vibration with respect to the input frequency and the corresponding phase. The frequency and phase analysis is almost entirely handled by hardware developed by John Abel. The algorithms to interpret and retrieve this information merely press the appropriate buttons to get the information from the Frequency and Phase Detector (FPD) circuitry.

The FPD hardware is currently in its second revision. The original revision utilized a Cypress 48-pin I2C GPIO expander (CY8C9540A). This GPIO expander proved to be overly complex to utilize and had improperly implemented the “Stop and Hold” aspect of the I2C protocol. One out of five times the CY8C9540A would use the “Stop and Hold” procedure it would fail to return to a proper state and the I2C bus for the entire payload would be driven to ground. This behavior was determined to be unacceptable and the CY8C9540A was replaced by two NXP Semiconductor 24-pin I2C GPIO expanders (PCA9555).

The detectFreqNPhase function begins by initializing the FPD hardware to specified state. It then switches the input read into the FPD hardware to the output of the specified beam. The FPD hardware is then cleared and armed, and the Input Frequency, Output Frequency, and Phase values are read into the microcontroller. Respective errors are flagged and the results are returned.



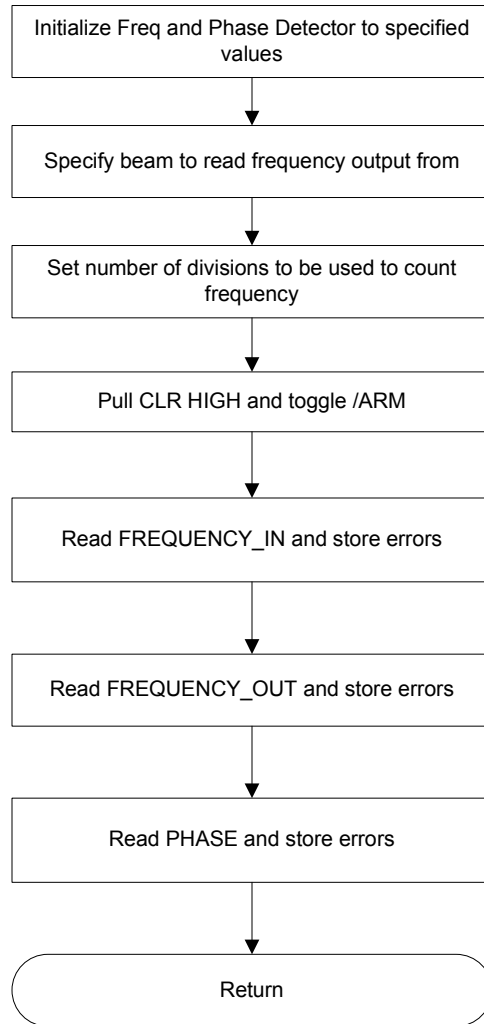


Figure 23: detectFreqNPhase overall flow chart.

The remaining portions of the function read in the input frequency, output frequency and phase. They all follow the exact same pattern to retrieve the data. The respective BUSY line is waited on to reach a low or inactive state. If TMAX is reached before it goes low and error flag is set. Either way the function proceeds to toggle the UPDATE\_CNT line and read in each byte of the four byte value beginning with the most significant. The bytes are shifted into return variables.

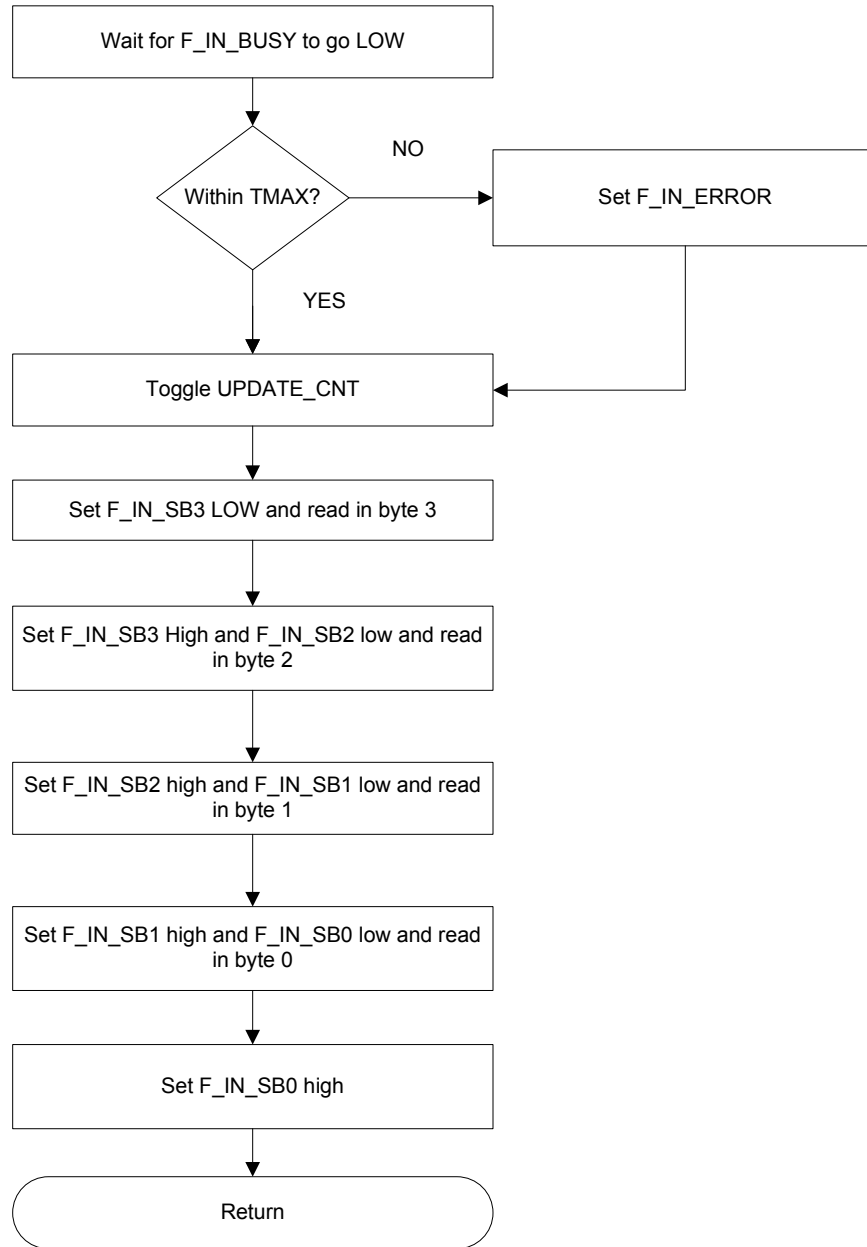


Figure 24: Frequency In evaluation.

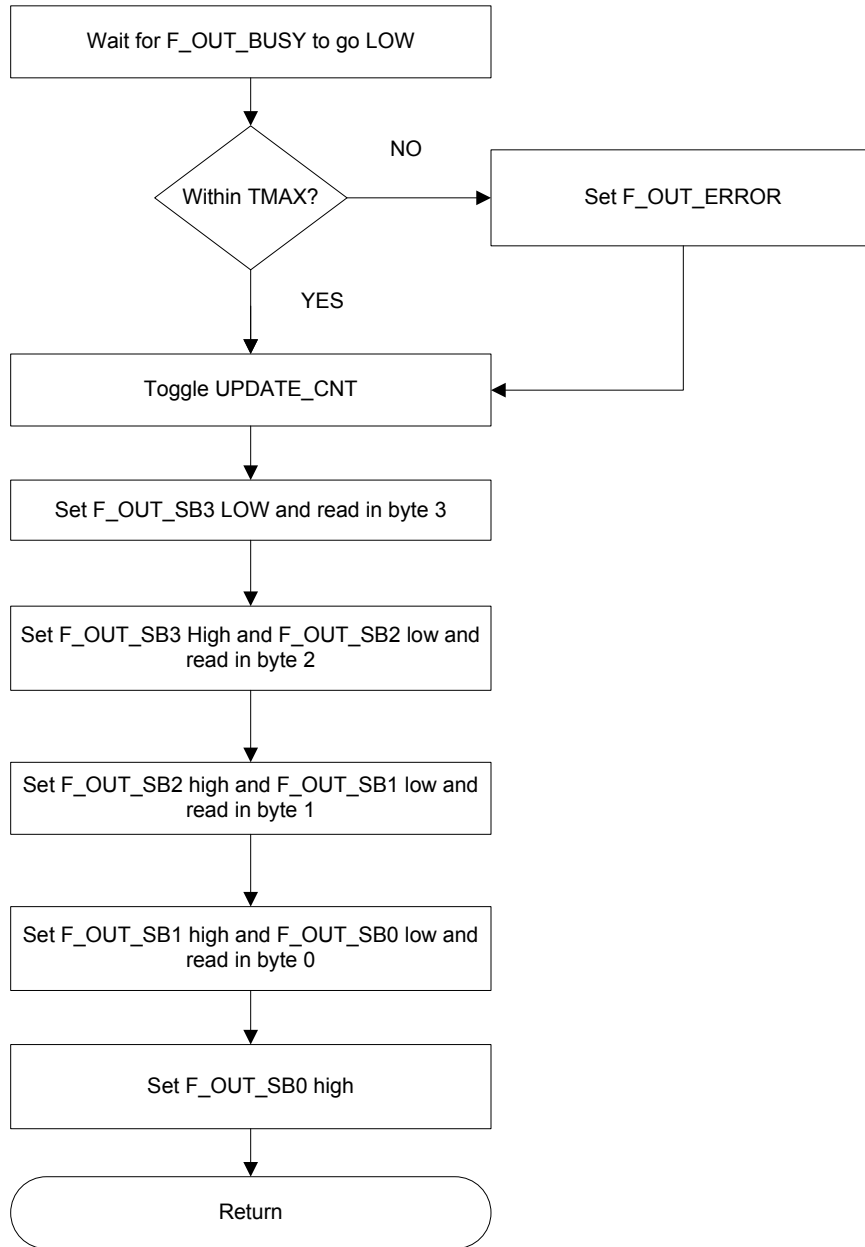


Figure 25: Frequency Out evaluation.

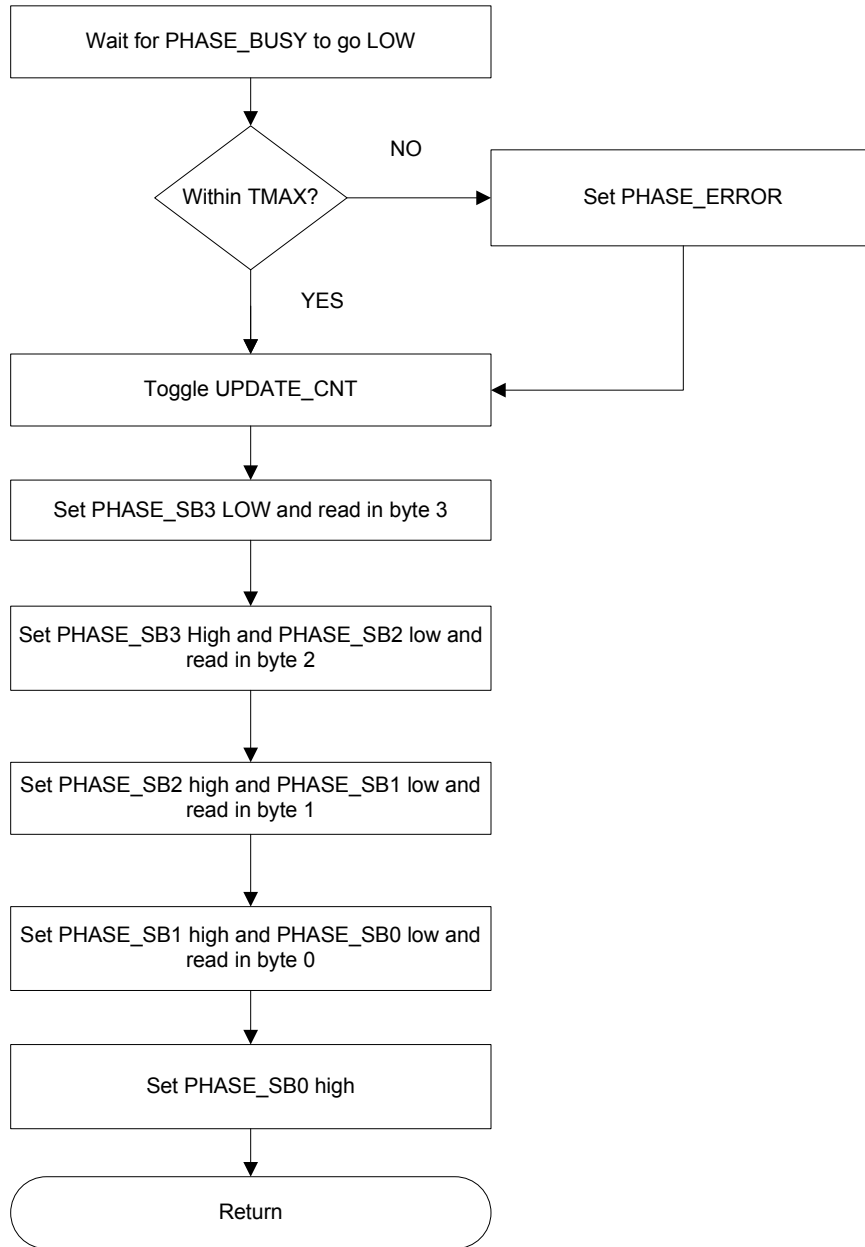


Figure 26: Phase evaluation.

### 3.7. Developing a test platform

The testing segment of the CP7 satellite is broken into two parts. The first part is the evaluation of beam behavior at a single frequency, single amplitude, and on a single beam. The second part is the ability to evaluate a single beam across a spectrum of frequencies at constant amplitude. It is important that if one component of the test fails that the failure is noted, remaining test data is not corrupted or disrupted, and all of the resulting data can be stored in the same form as a correct test sample. It is also important that the test utilizes the gain controls to maximize the accuracy of the data and that the test includes all the aspects of data acquisition available.

The `singleFrequencyTest` method runs with the expectation that the AD9833 has been properly initialized and configured and that `setCoarseGain` has been called placing the piezo driver board in a proper state for the test. The method sets the frequency to be output by the AD9833 and stores the frequency on the EEPROM. The wait and read time is reevaluated based on the current frequency. Depending on the `updateAmp` parameter the `updateInputAmplitude` algorithm is called or the `waitNRead` algorithm is called and the results are stored on the EEPROM. The I2C bus of the appropriate beam and the output lines from the peizo driver to the appropriate beam are selected. The automatic gain control for the sensor board is activated and the results of the automatic gain control process are stored on the EEPROM. The `findSteadyState` algorithm is called and the results are stored, and finally the frequency and phase are found and also stored on the EEPROM.

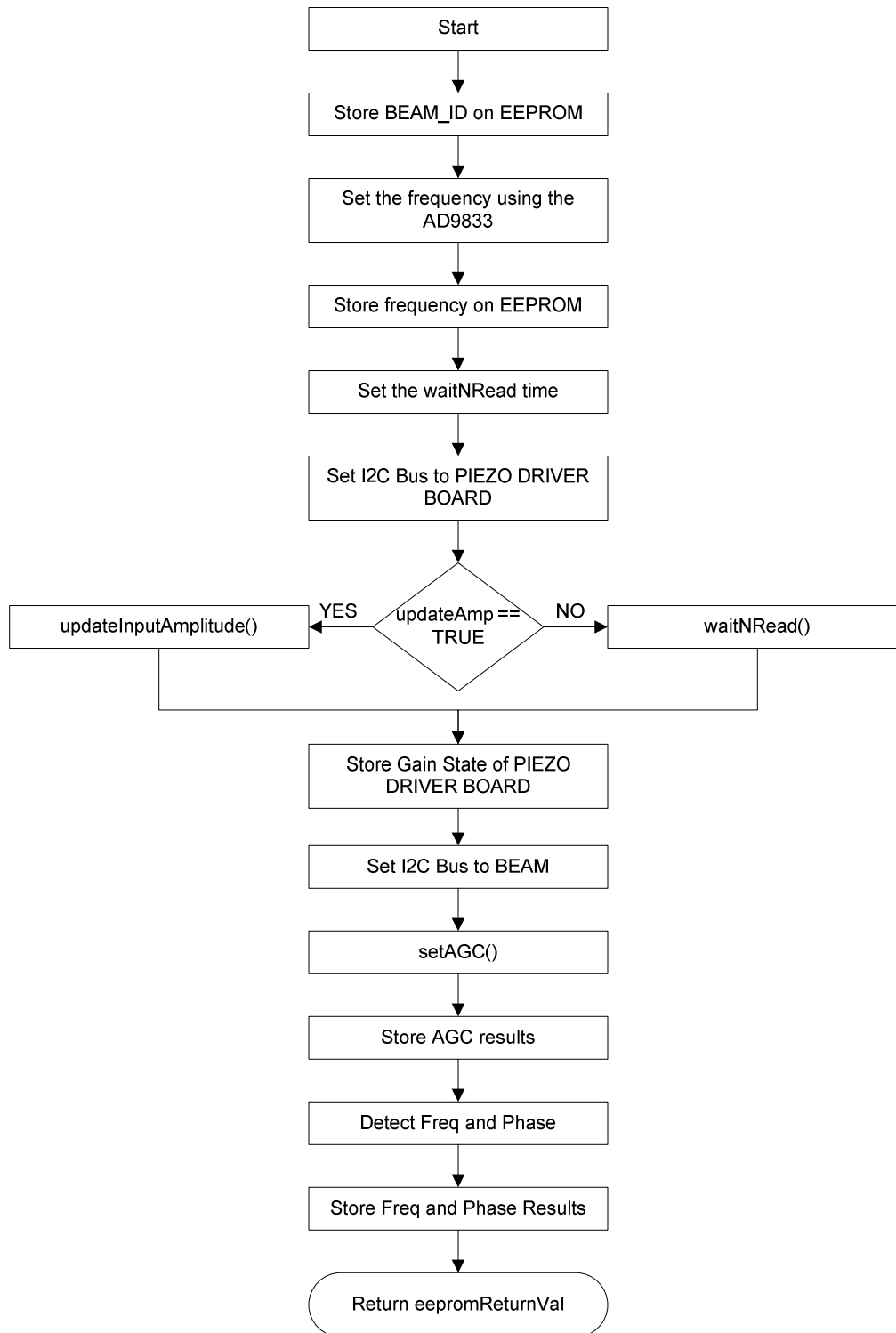


Figure 27: Single Frequency Test method.

The freqSweepTest method handles the preparation of the AD9833 and the calls the setCoarseGain algorithm. During the initialization period a significant amount of time is spent waiting for the hardware to reach a stable state. After the system has stabilized the singleFreqTest method is called with the parameters altered to achieve tests of the desired frequency spectrum.

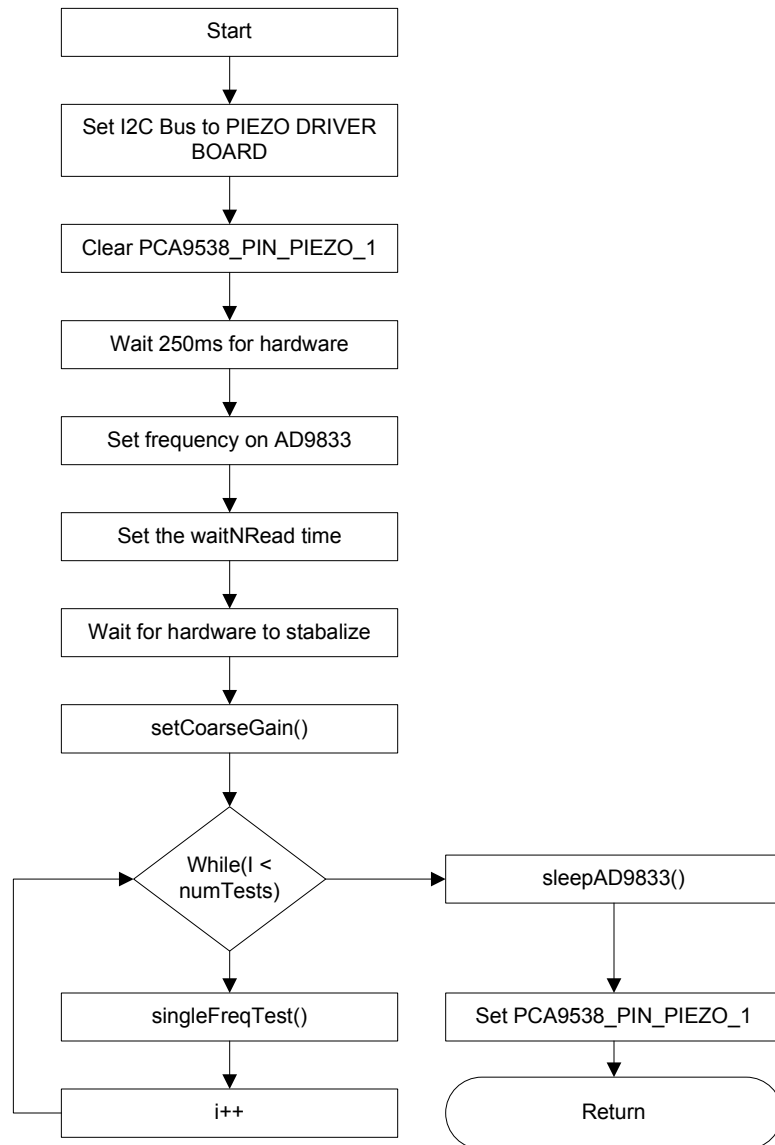


Figure 28: Frequency Sweep Test method.

## 4. Evaluation

The CP7 satellite currently exists as an engineering model. The structure for the three beams have been machined and assembled and are in testing. The entire structure, including all electronics, successfully completed preliminary vibration testing on 11/30/2010. The fact that the piezos survived the vibration testing is considered a huge success as it was a potential flaw in the system design.



Figure 29: CP7 Engineering Model without solar cells.



The piezo driver board has been shown to correctly produce waveforms with amplitudes from 10VPP to 700VPP. The design of the coarseGain, fineGain, and updateInputAmpl algorithms are designed to get the output waveform amplitude as close to the desired VSET as is possible to achieve with respect to the hardware. The maximum measured error has been roughly 2V for certain VSETS above 660VPP or a maximum 0.6% error. At this level the degree of accuracy for the measurements becomes blurred due to the limitations of the laboratory equipment. The response of the beam to these inputs can only be evaluated by the data retrieved from the sweep tests. Below is a graph showing the beam response at different frequencies and amplitudes. Note the response of the unfilled beam versus the filled beam clearly demonstrates the effectiveness of the particle dampener.

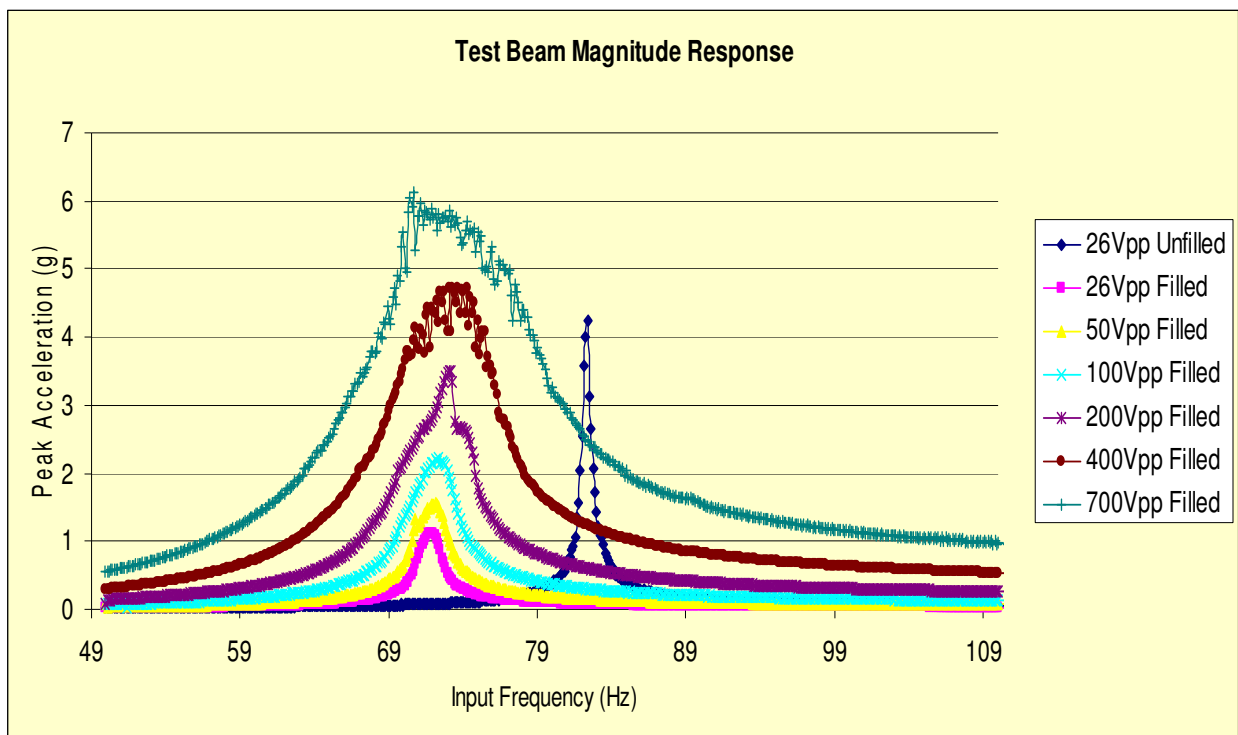


Figure 30: Magnitude response of the test beam.

The piezo driver board has been shown to correctly produce waveforms with frequencies between 10Hz to 200Hz. The scope used to measure the frequencies output by the piezo driver board could only measure to 0.01Hz accuracy and in this range it was found that the defined output frequency was

always achieved. Another important aspect of the piezo driver board's output frequency was the beams resultant frequency response. The frequency and phase hardware was able to measure the difference in output frequency to beam frequency to be less than one milli-hertz. Shown below are the frequency and phase plots resulting from a sweep test.

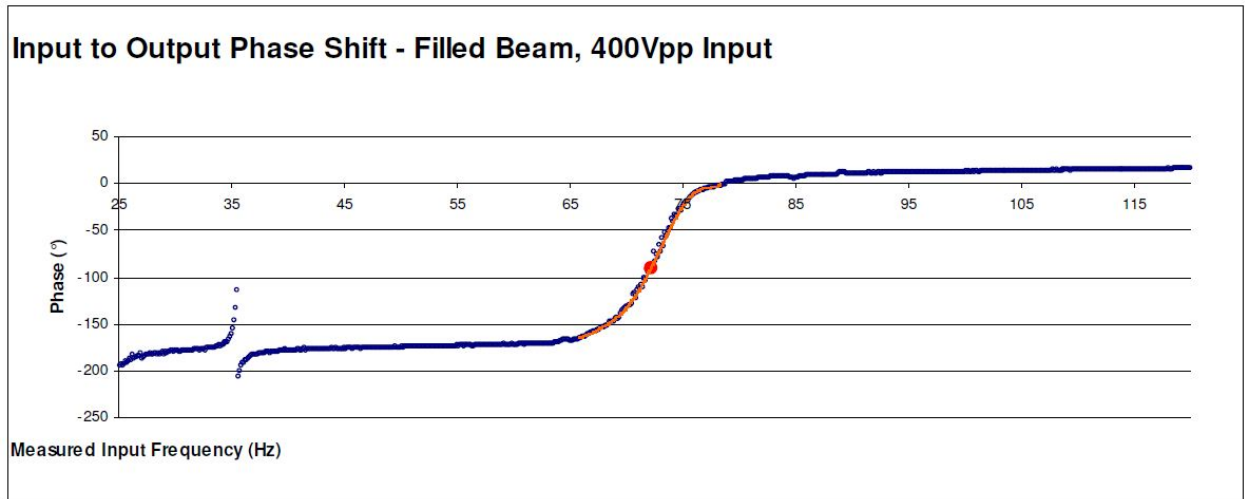


Figure 31: Phase response of the test beam.

The measured output of the sensor boards was calculated to be within 3 milli-G's of the expected output. This level of accuracy was made possible by the automatic gain control and the accuracy of the MEMs accelerometer. Below is a graph showing the beam response of multiple frequency sweeps across multiple amplitudes. The response is measured in G's per foot pound and the input amplitude is measured in foot pounds.

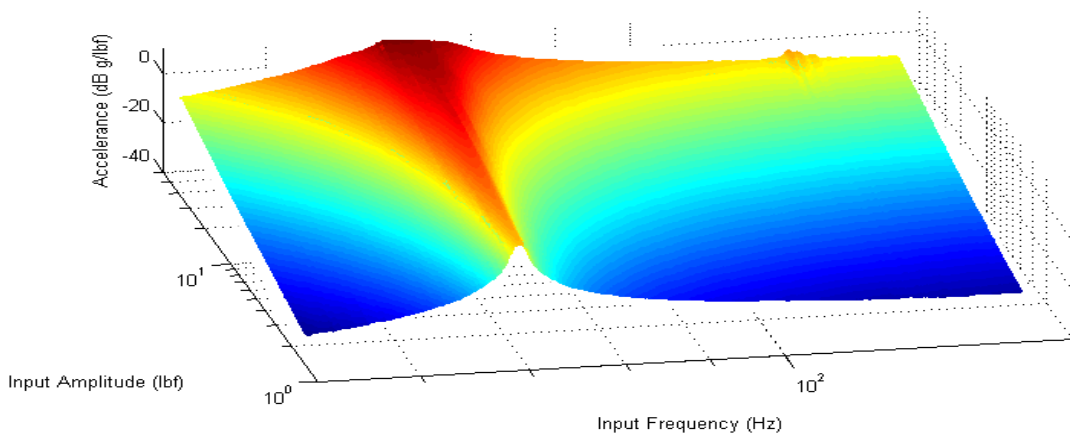


Figure 32: 3D graph of magnitude response of test beam.

A result of the NASA Zero-G Flight the steady state response was of particular concern. It has been found that steady state is typically found within 0.02G's. This includes in the highly unstable resonant frequency region when the particle dampener is generating the most nonlinear behavior. Below is a graph demonstrating the systems steady state tolerance.

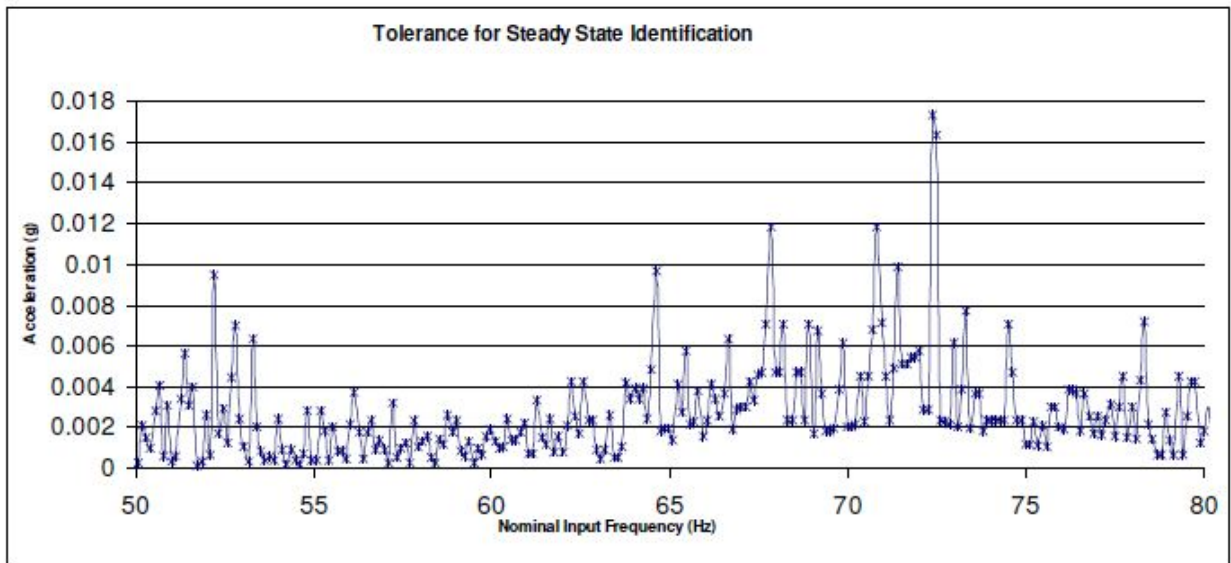


Figure 33: Steady state tolerance.

## 5. Conclusions

Working on the CP7 Payload Software was a significant and worthwhile undertaking. Many frustrating hours went into debugging hardware and software issues, but each of those hours proved to be full of unexpected learning opportunities. The multidisciplinary nature of the project and the excellent engineers working on the project added a great deal of value to the experience and I sincerely hope that future computer engineers will be able have similar experiences.

There are a number of things that will need immediate attention for the CP7 Payload Software. The Bus Interaction is incomplete and will need extensive development on both the payload side and the P-CAP side. An error flagging system has been described in detail in the code documentation, but still needs to be implemented. The beam locking algorithm needs to be updated to use timers and interrupts in conjunction with the current and temperature sensors to protect against failures of the shape memory actuators. No aspect of the watchdog timer has been implemented; this will need specialized attention and care to ensure no hardware loops are permitted. The full waveform capture on the sensor boards has not been fully implemented which is not necessary for mission success, but would add to the quality of test data. Memory usage is currently limited to one of the four EEPROMS, this could easily be expanded by implementing a memory management algorithm and memory read and write methods. The accelerometer self test feature currently has a method in place, but has not been tested due to a VVAL hardware failure over the summer.

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