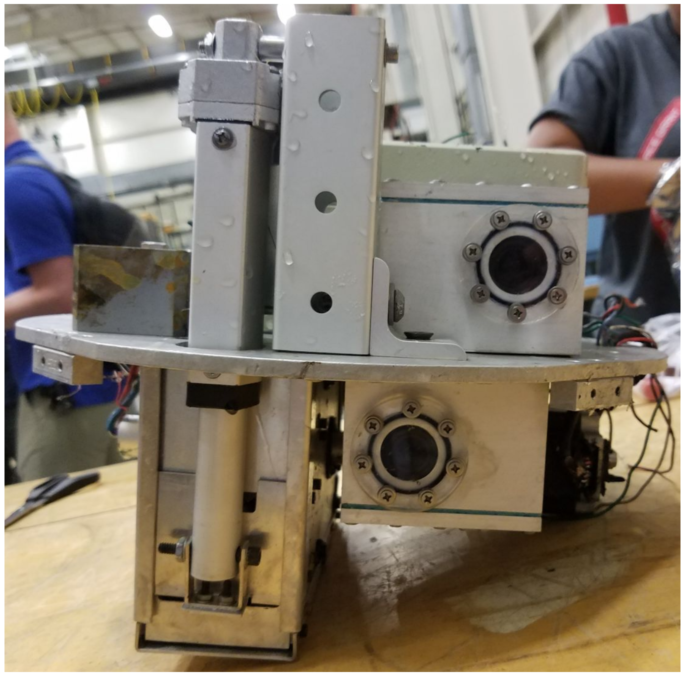
RockSat-X 2019 Final Report

UNL RockSat 2018-2019



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1.0 Mission Statement

The University of Nebraska - Lincoln looks to further develop and streamline the mechanism for a deployable boom system started by NASA Langley Research Center. To date, there is no easily integrated retractable boom system for suborbital platform experiments. This project seeks to fulfill the need for a standardized retractable, powered experiment platform.

This project hopes to provide a hands-on flight project experience for undergraduate students, develop professional and leadership skills of the team, engage students in a multidisciplinary project environment, and investigate a scientific and/or technological concept that is relevant to NASA and its strategic goals. To verify the success of the system, video and sensor readings of the mechanical systems will be taken during deployment and retraction of the boom. More specifically, the payload should deploy the boom 4 times the payload footprint, it should collect and store video and sensor data, it should telemeter sensor data of deployment during flight and lastly, restow and lock boom.

The need to deploy and retrieve payloads from sounding rockets was identified as a project of value by NASA's Wallops Flight Facility (WFF). NASA's Langley Research Center (LaRC) is particularly interested in the ability to deploy and re-stow solar panels from a sounding rocket. Broadly, this research theme supports NASA strategic priorities as listed in the 2014 Strategic Plan [NASA 2014]: enabling aeronautics research (Objective 2.1), enhancing knowledge of Earth as a system (Objective 2.2), strengthening the education and workforce pipeline (Objective 2.4), and cultivating future workforce (Objective 3.1).

2.0 Mission Requirements and Description

The University of Nebraska-Lincoln and NASA Langley partners determined the specific requirements for success and additional objectives desired to be achieved. For the minimum success criteria the team would need to accomplish:

- Extend the Payload four times the payload footprint (~6 feet)
- Retract, stow and lock the boom in place to be able to retrieve safely upon re-entry
- Obtain Inertial Measurement Unit (IMU) data and data that proved the experiment successfully extended and retracted.

For further information and data collection the Comprehensive Success Criteria was decided on in addition to the Minimum Success Criteria :

- Mechanical verification of extension of boom
- Obtain data specified by collaborators
    - Retroreflective target on the end of boom with a camera system to analyze the data with photogrammetry

The University of Nebraska-Lincoln (UNL) RockSat-X 2018-2019 team decided to amend and try a similar experiment to the UNL 2016-2018 USIP project team but improve upon the design and outcome. The payload's focus was to deploy a SHEARLESS boom designed by NASA Langley researcher Dr. Juan Fernandez.

The main mission for the mechanical team was to create a housing for the boom so that it could easily deploy and retract without blossoming, esure the end-effector and end of the boom would be stowed and protected during reentry, create custom GoPro housings to protect the GoPro's SD cards during reentry and splash down in the ocean, and to keep the payload's weight and center of gravity within specific parameters given by Wallops.

The electrical team's main responsibilities were to control all systems onboard the payload. This included interpreting the rockets signals, triggering the two GoPro cameras, controlling the motor, and recording IMU sensor data on board. Additionally, all of the data needed to be stored onboard or telemetered back to Earth for post processing, this was also covered by the electrical team's objectives.

3.0 Payload Design

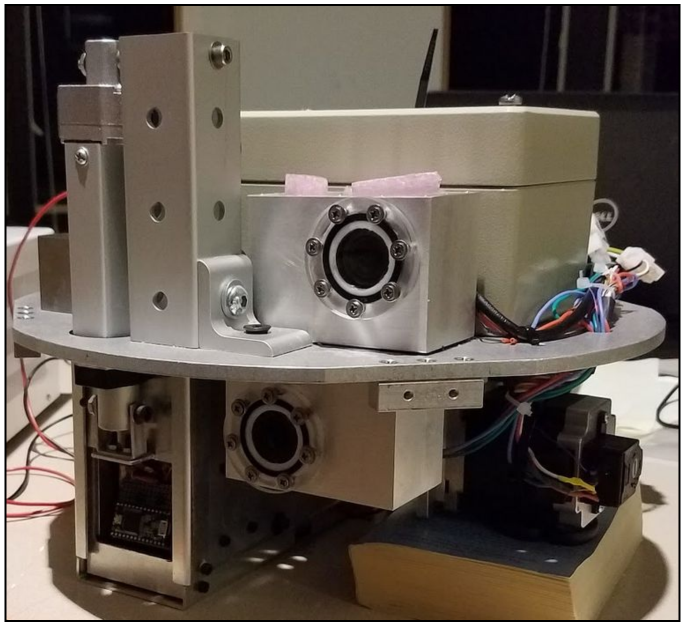

Figure 1 - Final Configuration of the UNL RockSat-X Payload

The final payload shown in Figure 1 was developed in two sub-system assemblies:

1. Mechanical and Hardware
Focused on developing the mechanical device for storing, deploying and retracting a composite SHEARLESS Boom and interface hardware for attaching components to a composite boom. Housings, mounting and ballasts for the rest of the equipment required to meet minimum success criteria.

2. Electrical and Software
All electrical components for controlling payload hardware and logging relevant data, including cameras, accelerometers, gyroscopes and a means of data storage. Development of the software to interpret signals and logical control of electrical and mechanical hardware.

For the mechanical design, tape springs are among the simplest forms of deployable structures used for spacecraft. Tape spring booms can be fabricated from a variety of materials including stainless steel and carbon fiber reinforced polymers. Tape spring booms are designed to be stowed by coiling around a spindle, which makes them especially compact compared to other deployables. In their extended configuration, the booms' cross section has a curvature that allows it to support axial force along its length. UNL's retractable deployment mechanism was designed specifically for use with the 1.85 inch (45.5 mm) wide composite SHEARLESS boom developed and patented by Dr. Fernandez at Langley Research Center. The SHEARLESS boom consists of two separate carbon fiber strips held inside a close fitting flexible sheath made of fluorinated ethylene propylene (FEP) plastic. In its extended configuration, the SHEARLESS boom has a lenticular (biconvex) cross section.

The boom deployment mechanism is pictured in Figure 2. An acrylic sheet is used here to show internal components. In flight, an aluminum sheet takes its place.

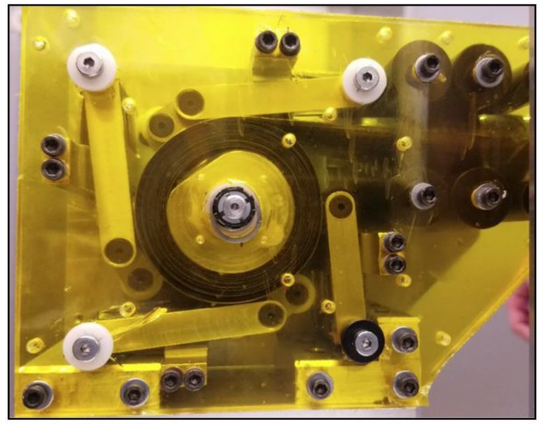
Figure 2: Deployment Mechanism Internal Components

Many of the features of this deployment mechanism were adopted from mechanisms developed for similar tape spring booms. A critical feature of these deployment mechanisms is a set of four to eight compression rollers that apply force against the coiled boom to keep it tightly wrapped around its spindle. Rocker arms apply force against the rolled boom through the compression rollers via torsion springs. Three of the rocker arms have two rollers each, and a bogie keeps both rollers in contact with the roll at all times. With this rocker arm configuration, there are always seven points of contact against the rolled boom.

"Blossoming", seen in Figure 3, refers to the failure of the boom to deploy when the amount of opposing axial force on the boom causes the layers of stowed boom still on the spindle to slip past one another and to begin expanding inside the deployment mechanism. The spindle will continue to turn, causing the stored boom to expand inside the housing. This may result in damage to the boom.

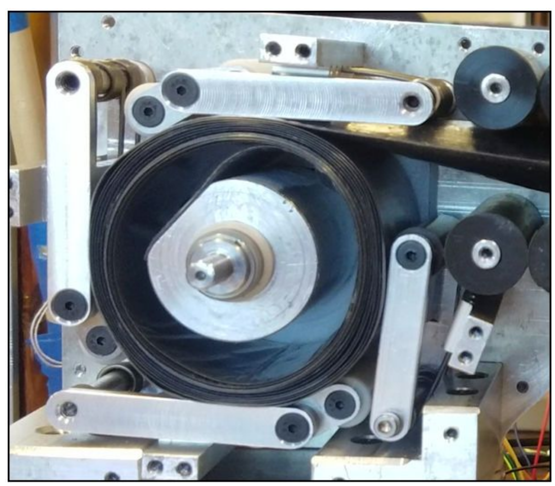
Figure 3 - Blossoming

Initial testing of the deployment mechanism resulted in failure of the boom to deploy against the force of the friction of the boom on the rollers and the weight of the end effector. With the compression rollers applying two pounds of force against the roll, the extended boom could only withstand 1.1 pounds of compressive force before blossoming would occur. Different torsion springs were used in the rocker arms so that each compression roller applied 7 pounds of force against the roll, but the amount of compressive force that the extended boom could withstand did not increase appreciably.

Further investigation into the blossoming led to testing with one side wall removed in order to more closely observe the blossoming issue, shown in Figure 2. It was identified that the layers of the boom would begin to slip and slide past one another before a large amount of blossoming would occur. If this slipping between layers could be prevented, blossoming could not occur. A simple solution to increase traction between layers of the boom was the addition of double adhesive backed Kapton tape. Kapton has a long history of reliable use in space applications, and its implementation required no change to the existing design.

Figure 4 -Kapton Tape on the Boom Sheath

Swatches of 0.5 inch wide double sided Kapton tape were applied in pairs to the bottom side of the boom every 4 inches to ensure Kapton on every layer when stowed on the spindle, seen in Figure 4. After implementing the Kapton tape, the boom deployed the end effector multiple times reliably. Blossoming testing determined the new back force on the boom before failure to be 7.8 pounds of force. However, when blossoming with the tape did occur, it would cause damage to the boom and a disassembly was required to correct the issue.

The boom is attached to the deployer at the spindle which rotates on PTFE sleeve bearings. The spindle is hollow inside to allow an electrical slip ring to fit inside. Wires from the slip ring pass through hole in the spindle near the boom mounting point. These wires, seen in Figure 5 pass between the carbon fiber leafs and go the full length of the boom to the end-effector to allow electrical power and signals to be passed from the end of the boom to the electrical housing. Two small screws pass through the sheath, the two carbon fiber leafs, into threaded holes in the aluminium spindle. As a precaution rubber washers are used to distribute the clamping force on the boom to prevent tear out.

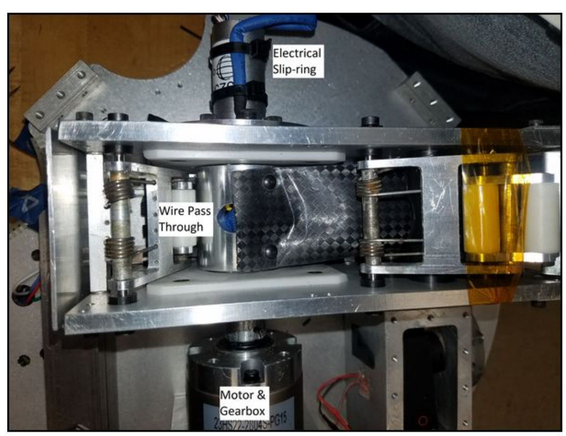

Figure 5 : Electrical Wire Pass Through

A stepper motor was chosen to deploy the boom for its high torque and precision positioning. The stepper motor was fit with an encoder for functionality verification and 15:1 gear ratio planetary gear system to further increase torque. A collar slipped over the gearbox shaft and the spindle shaft and was secured with a spring pin to allow the two to interface with each other to transmit torque. With this setup the boom could easily be deployed at a rate of 2.5 in/s but this was limited to 1.2 in/s at the request of the launch vehicle provider.

To prevent the loss of the end-effector and the end of the boom the deployer was designed to allow the end effector to be retracted inside the deployer housing. The front rollers were designed to have an indentation for the end-effector mounting hardware to be tightly held in place when the boom fully retracted preventing the end effector hardware from moving up, down, left, right, or from retracting any further in the axial direction. The end effector in the stowed position could only be moved in the deployment direction once the boom was deployed. Angled sheet metal ramps on the interior guided the end effector to ensure it did not get caught on any hard edges. After the boom deployed and retracted, the sheet metal door in Figure 6 was closed over the opening to prevent hot and violent re-entry winds from melting the boom and end-effector and from causing it to rip off.

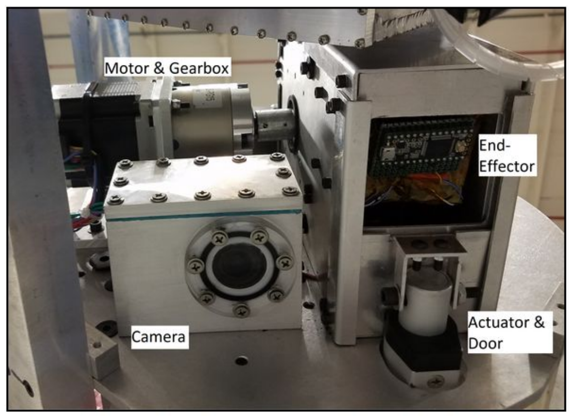

Figure 6 : Deployment Side of Payload

A GoPro Hero 3 Black edition was selected to record video data for visual verification and stereo-vision analysis of the boom deployment dynamics. Standard GoPro waterproof housings were not expected to survive the high heat and violent forces of reentry and retain their integrity for keeping out sea water. Two aluminium housings were designed, seen in Figure 6, to keep the cameras safe. A hole in the front of the housing allowed the GoPro lense to orienented in the housing. Around this hole a pattern of screw holes were placed to allow an acrylic clear lens covering to be tightly secured against a standard O-ring to prevent air and water seepage. The interior of the housing was made with a large enough gap to allow the camera to be inserted and then have thermal foam packed on all sides to secure the camera in position as well as protecting against the high heat of re-entry. The lid was made with a tight screw pattern around the top of the housing. A custom gasket was designed and ordered to use the maximum surface area between the lid and housing body. To allow electrical signals to pass through the housing a small 1/8th inch hole was drilled through the quarter inch thick wall on the back side of the housing. Wires were passed through this hole and then sealed with epoxy to create a air/water proof seal. Each housing was attached to the plate with four screws that threaded into mounting holes on the bottom of the housing.

Electrical systems in space applications require special consideration. The lack of pressure can cause many electrical components to fail or behave strangely. One of the largest concerns is arcing. Earth's atmosphere provides enough dielectric strength to prevent arcing of high voltages at small separation distance. However, in a vacuum, even low DC voltages can be problematic. To protect the main electronics from these problems, a sealed off the shelf housing was modified to maintain an artificial atmosphere seen in Figure 7. For the electronics mounted on the end of the boom, a conformal coating was used to prevent arcing.

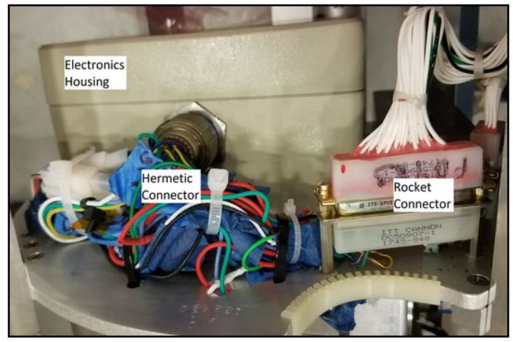

Figure 7 : Electrical Housing and Connectors

The main electrical components were located in an aluminum housing above the deployment mechanism (Figure 7). There was a hermetically sealed connector that gave the electronics wires access to the components outside of the electrical box. The wires were epoxied into place so that stress would be moved away from the solder joint and onto the bulk of the wire, allowing for a solid connection.

Power was provided via three 28 volt DC lines. The first line was active at T-180 (180 seconds prior to rocket motor ignition) and powered the processor and support hardware. The second started at T+0.01 (0.01 seconds after rocket motor ignition) and were used as signals for the GoPro cameras. The third, meant to power the motor driver exclusively, started at T+110. This was done to ensure too much current was not pulled from a single line.

The motor selected was a NEMA 24, 8-wire bipolar stepper motor. It was driven using a dual h-bridge, with one bridge per winding. To achieve closed loop control of this motor system, an optical encoder was mounted on the spindle shaft. This was used to ensure that the motor wouldn't extend farther than it needed to. While the boom deployment speed was constant during this mission, there is room for improvement for a closed loop speed control. This would be done with redundant encoders and accelerometers.

The deployment and retraction phases were controlled during flight testing via a step counter rather than the planned closed loop control. The deployment phase lasted 60 seconds and was designed to deploy approximately 6.0 feet. After a 60 second dwell, the retraction phase occurred. The entirety of the critical experiment window lasted for 180 seconds.

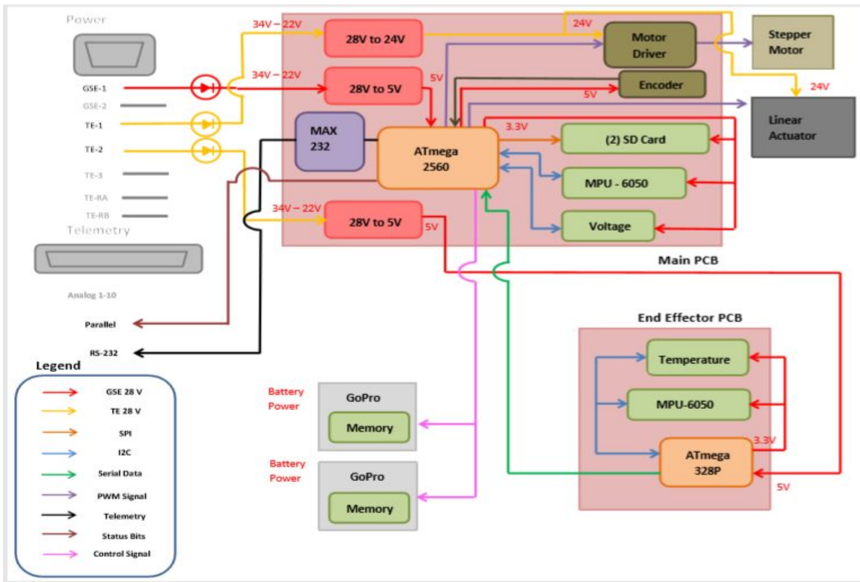

Figure 8: Functional Block Diagram

The primary method planned to confirm mission success was IMU (inertial measurement unit) data. Rotations, accelerations and temperature sensors were used to collect data. IMUs offer three axis accelerometers, and gyroscopes all in a single chip, and function by measuring linear acceleration (see Figure 8 for block diagram). One IMU was mounted inside the housing while the other was mounted on the end of the boom on the end effector. These were primarily used to calculate deflection angle of the boom as it deployed. A major disadvantage of using IMUs was that they typically suffer from accumulated error. This can be adjusted for by using a complementary filter, but this was not implemented due to the short nature of the experiment and trouble with the implementation. Data from the IMUs and cameras were all set up to be logged internally.

The secondary means of verification were video from the two GoPro cameras mounted on the payload deck. They were both set to record 68 seconds after launch until the end of the mission at T + 310 seconds. GoPros were selected for their ease of setup and ability to capture high resolution video. To assist in the post-experiment interpretation of these video a visual target, seen in Figure 9 was created and mounted on the end effector. This target used retro reflective material for backing with black electrical tape used to create crosses with known distances for scale in post processing. Also, leds with different colors were mounted to the corners and lit as additional points of measure that illuminated themselves. Cameras were activated by an electrical

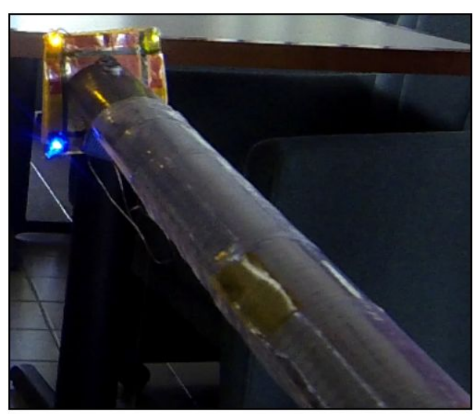

Figure 9 : Boom & Visual Target

relay soldered to the power button terminals and controlled by a Teensy microcontroller. The microcontroller closes the relay to simulate pressing the power/record button on the GoPro. A physical logic inhibit was added to tell the microcontroller not to turn on cameras during sequence testing to conserve battery and storage. This was removed before flight, enabling the cameras to record during flight.

4.0 Student Involvement

All students involved in the UNL RockSat 2018-2019 can be seen listed below:

Renick Wilson (Mechanical Engineering) - Team Lead - Had administration responsibilities, including handling the team's financial situation, recruiting, main correspondance with Faculty Advisors and Mentors, and lastly to help out with any mechanical design

Michael Cox (Mechanical Engineering) - Mechanical Lead - Main responsibility was to oversee the mechanical design of the payload, deal with all mechanical team's financial issues, and delegate work to the rest of mechanical team. Additionally, presented in all review meetings to RockSat regarding all things Mechanical. Michael graduated in Fall 2018 and was replaced by Ryan Green.

Ryan Green (Mechanical Engineering) Mechanical Lead - Main responsibility was to oversee the mechanical design of the payload, deal with all mechanical team's financial issues, and delegate work to the rest of the mechanical team. Additionally, presented in all review meetings to RockSat regarding all things Mechanical. Ryan also helped out the electrical team design the motor controller and camera trigger systems.

Zoe Marzouk (Mechanical Engineering) - Mechanical Team - Assisted with all mechanical design.

Phoebe Pena (Biology) - Mechanical Team - Assisted with all mechanical design.

Tom Faulconer (Electrical Engineering) - Electrical Lead - Main responsibility was to oversee the electrical/software design of the payload, deal with all electrical team's financial issues, and delegate work to the rest of electrical team. Additionally, presented in all review meetings to RockSat regarding all things Electrical.

Aaron Hayes (Physics) - Helped design mission software for the electrical team.

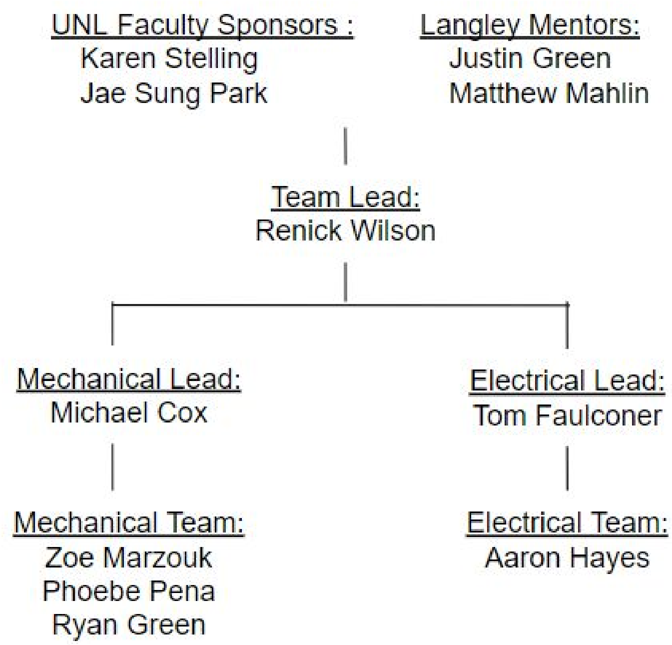

Figure 10: Undergraduate Team. (From Left to Right) Ryan G., Pheobe P., Zoe M., Aaron H., Renick W., Micheal C., Pheobe P.(repeat), Tom F.

5.0 Testing Results

Before the launch multiple full mission simulations were completed for verification. For the final full mission simulation, a single power supply was used to simulate the rocket power source. All timer events were triggered by hand by manually connecting timer event lines to power at approximate times using a stopwatch. The boom deployment distance was verified with a tape measure to 6ft +/- 0.5 in. After the first several feet, the boom was supported against gravity by hand using a thin copper wire.

During the simulation, cameras turned on and recorded at proper times, and the recordings lasted for the full mission. The video was turned off and stored at the end of the mission. During stationary testing, the camera inhibit was tested and functioned as expected. The cameras and their triggering systems functioned as expected before flight. After testing, full batteries and empty SD cards were inserted before the cameras were sealed for the final time before flight.

Below are graphical representations of the data collected during testing. Shown first are the data for the main board MPU, and the second set are the data for the end effector MPU, followed by the motor encoder data. Descriptions of each data set are provided below the graphs they describe. For each graph, the x-axis is on the rocket time scale. T-0 is launch, and positive time values represent time since launch. Figure 11 defines the coordinate system in relation to the payload.

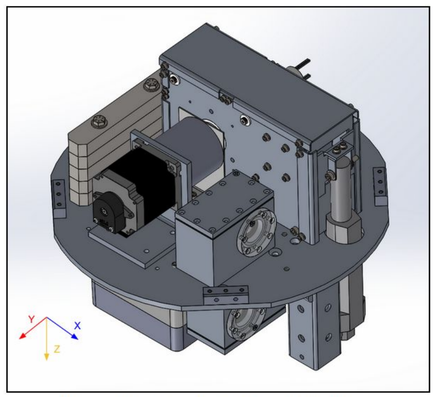

Figure 11 : Coordinate Axes Definition

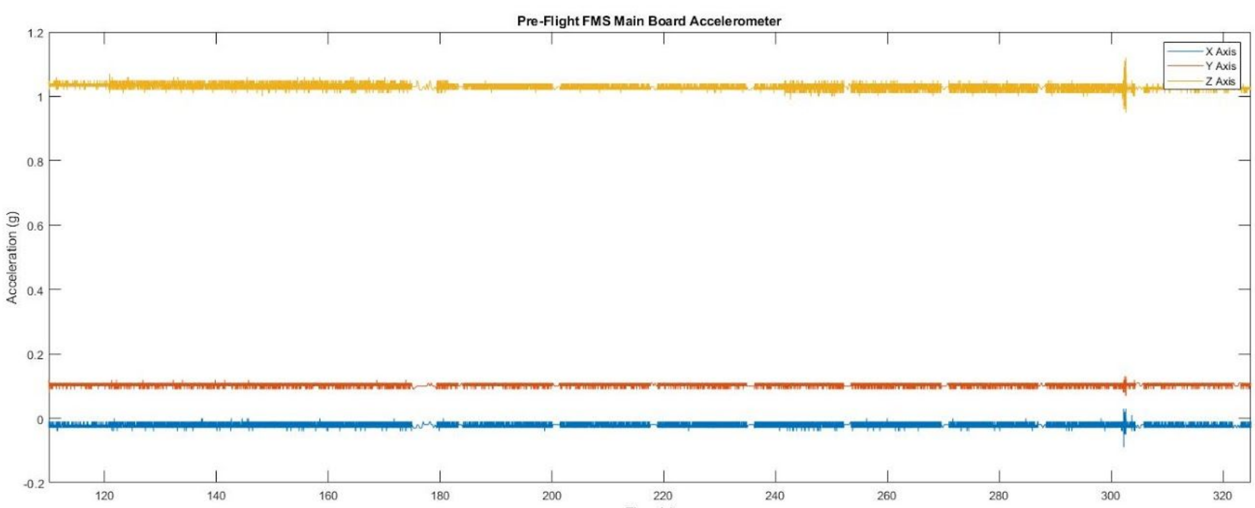

Figure 12: Accelerometer Data of Rocket Mounted IMU Pre-Flight

Figure 12 shows accelerometer data from the IMU mounted inside the main electronics housing that is attached to the rocket. As expected there is 1g measured on the z axis, the other values read near zero with a small offset that may be attributed to sensor error or the payload not being completely level. Near the end of the experiment a small disturbance can be seen due to the activation and closing of the actuator door.

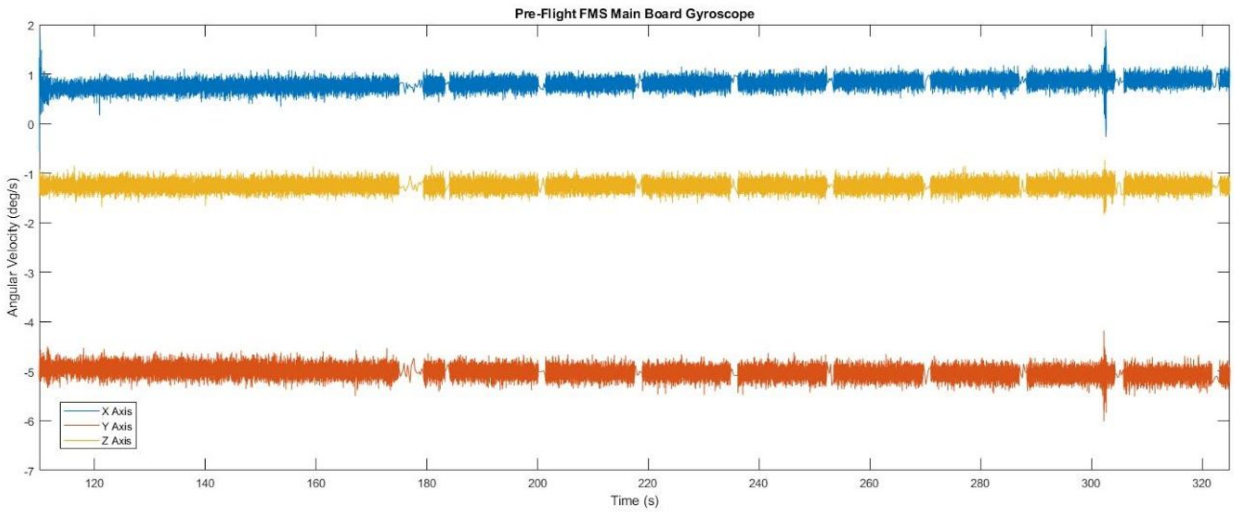

Figure 13: Gyroscope Data of Rocket Mounted IMU Pre-Flight

The graph in Figure 13 is the gyroscope data from the same IMU mounted in the main electronics housing. There is a consistent gyroscope offset error in the sensor. Main board electronics were stationary during testing, showing little change in values.

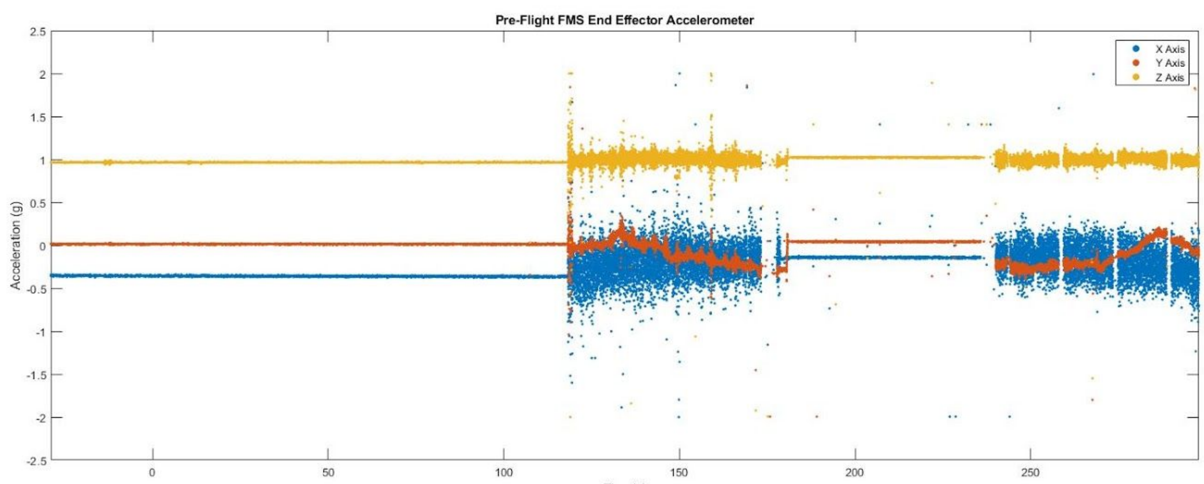

Figure 14: Accelerometer Data of End-Effector IMU Pre-Flight

An error in the software caused data collection to occur as soon as the power is turned on before launch (T-0). Since this did not cause a failure to collect the necessary data, the bug was not prioritized and was not fixed in time for launch. Noise in the connection caused some erroneous data points, but these made up only a fraction of the total data collected. In Figure 14 accelerometer data from the end of the boom is plotted. The distinct periods of deployment, dwell and retraction can bee seen as expected.

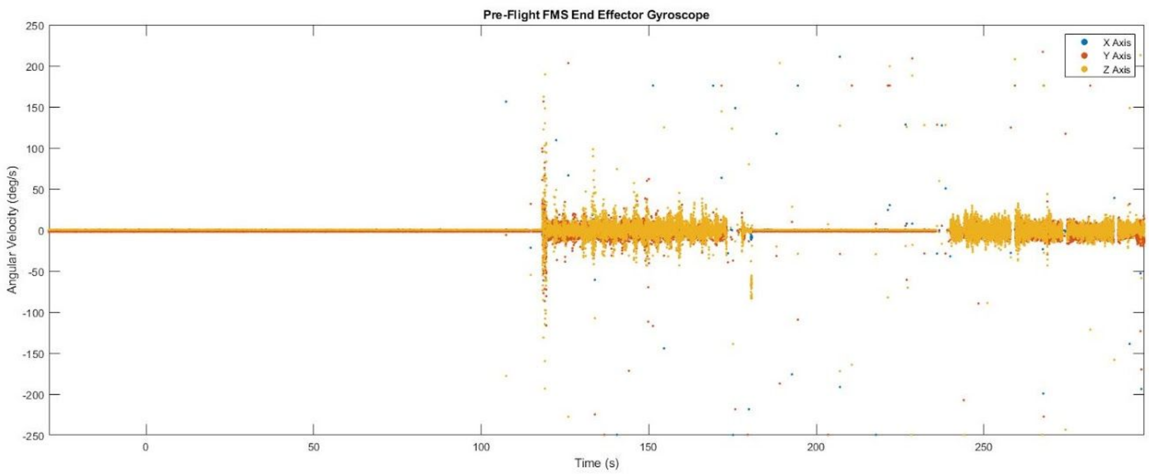

Figure 15: Gyroscope Data of End-Effector IMU Pre-Flight

Figure 15 shows angular velocities of the end of the boom. As expected the plot shows an average of near zero around all axis.

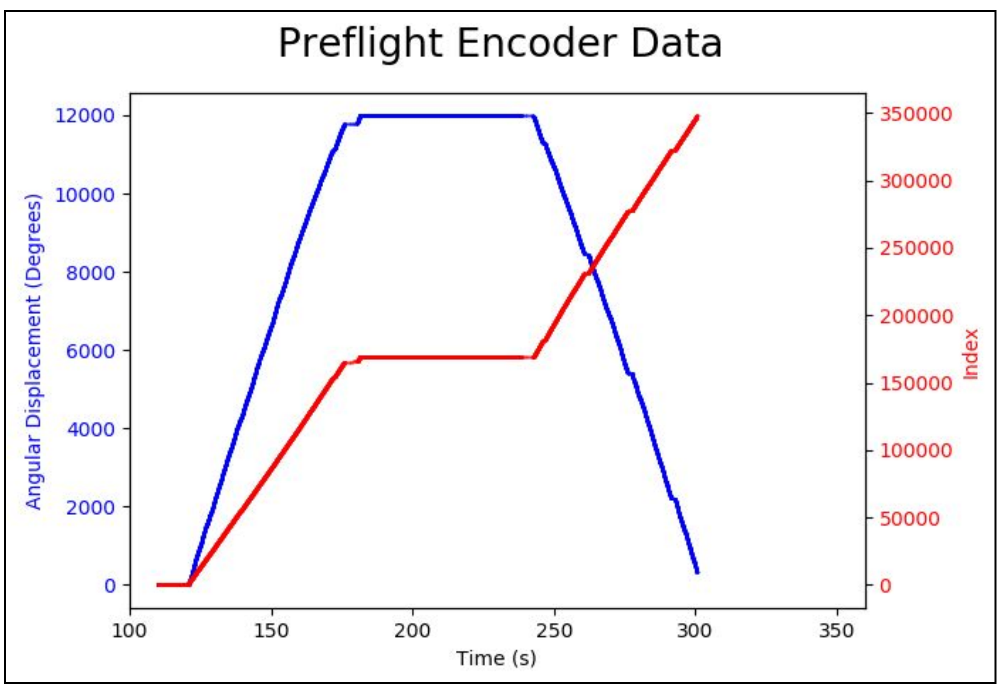

Figure 16: Motor Encoder Data

The encoder measured the angular displacement of the motor drive shaft plotted in Figure 16. The index pin on the encoder is an additional output which is supposed to increase once per full revolution. However, when recorded, the values exceed the angular displacement measurements. In spite of this unexpected result, there is still a correlation showing when the motor is turning and when it is stopped for dwell. This plot clearly shows the motor turning out for deployment, stopping for dwell, then returning to the same angular position for retraction.

Approaching the deadline for check-in, the payload was deemed fit for launch after two consecutively successful full mission simulations, determined by the activity of the mechanical components during testing as well as the data returned to the SD card. The team would be satisfied with data collected during launch that reflected that of the two successful full mission simulations.

6.0 Mission Results

The RockSat-X rocket launched on August 12th at 5:45 am from NASA Wallops Flight Facility. Launch, splash down, and recover happened as expected. Later the same day the payloads were deintegrated from the rocket and returned to their respective design teams.

The UNL payload was returned, seen in Figure 17 with much of the exposed wiring missing or melted as expected. The actuator door was fully closed and the end effector and boom could be seen inside through the cracks in the door. Upon opening the electrical housing and fore GoPro housings no water was seen to have penetrated and their SD cards were recovered without issue. During the opening of the aft GoPro housing some moisture was observed inside the housing but in small amounts. It is possible some water trapped in the gaskets got inside while removing the lid. As a precaution the SD card from this card was allowed to dry for several days.

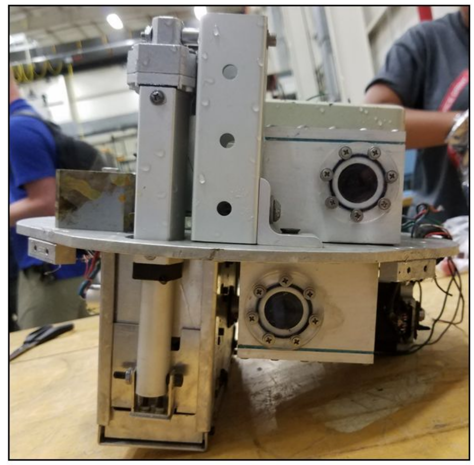
Figure 17 : Payload After Recovery

After reviewing the existing camera video and sensor data, it shows that we did not meet our minimum success criteria. Video recorded only occured after the mission during reentry. Sensor data for the end effector records before launch, during launch, and for some time into the mission timeline but during a critical point just at the start of deployment the data stops recording. Without these means of deployment verification we fail to meet minimum success.

Cameras were set to trigger at T+68 seconds after the launch forces had diminished. Then the cameras would record through skirt deploy, into mission start, recording the boom deployment, dwell and retraction. Then the cameras would shut off to save their footage. However, what can be seen in the video that was recorded are the final moments of the flight during reentry. The cameras record the descent of the rocket, it's parachute deployment, splash down, and continue to record under water until the batteries died.

An analog telemetry line was connected in parallel with the trigger signal to turn on the cameras. In Figure 18, shows a plot of the camera trigger relay voltage (connected to Analog 2 pin) throughout the duration of the mission. The relay uses a low logic TRUE signal to trigger the cameras and start recording. From GSE power on at T-180 s to power off at T+335 the camera relay is never triggered by the microcontroller. This resulted in the cameras failing to turn on during the mission. The most probable cause of this failure is that the circuit used to inhibit the cameras for sequence testing and enable for flight malfunctioned on launch and caused the microcontroller system to believe it was still in sequence testing. The reason the cameras recorded reentry and splash down is probably do to the wires to the cameras being stripped of their insulation from the high heat and winds of reentry and making the trigger wires cross.

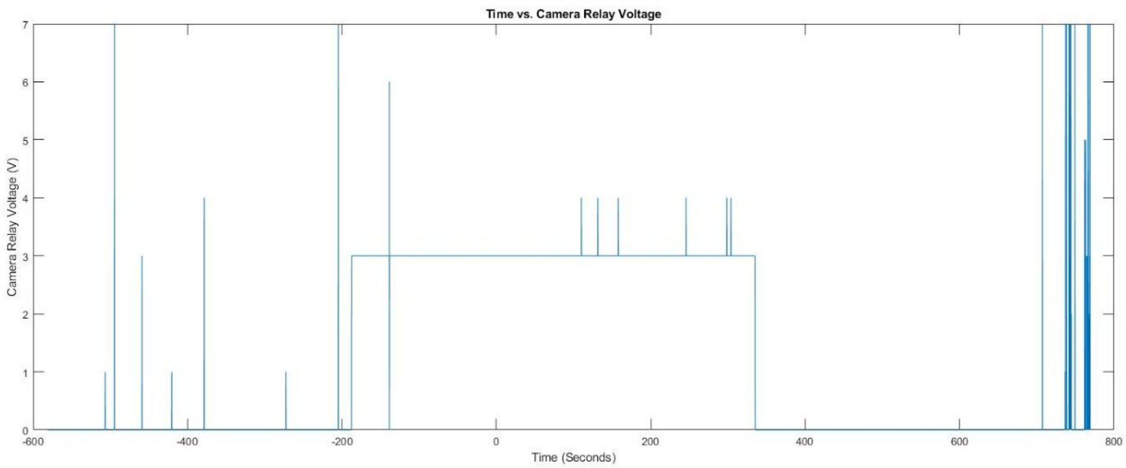

Figure 18: Camera Relay Trigger Voltage

Data recovered from the IMU in the electrical housing attached to the rocket is plotted in Figure 19. For axes reference see Figure 11. The X-axis is on the mission time scale with T-0 is the launch of the rocket. A similar graph to the full mission sim was expected. Nearly zero gs are measured on all axes, which indicates the payload is in a microgravity environment. The small spike around T+305 is at the correct time and magnitude to be caused by the actuator door closing. Nothing out of the ordinary was seen on this plot.

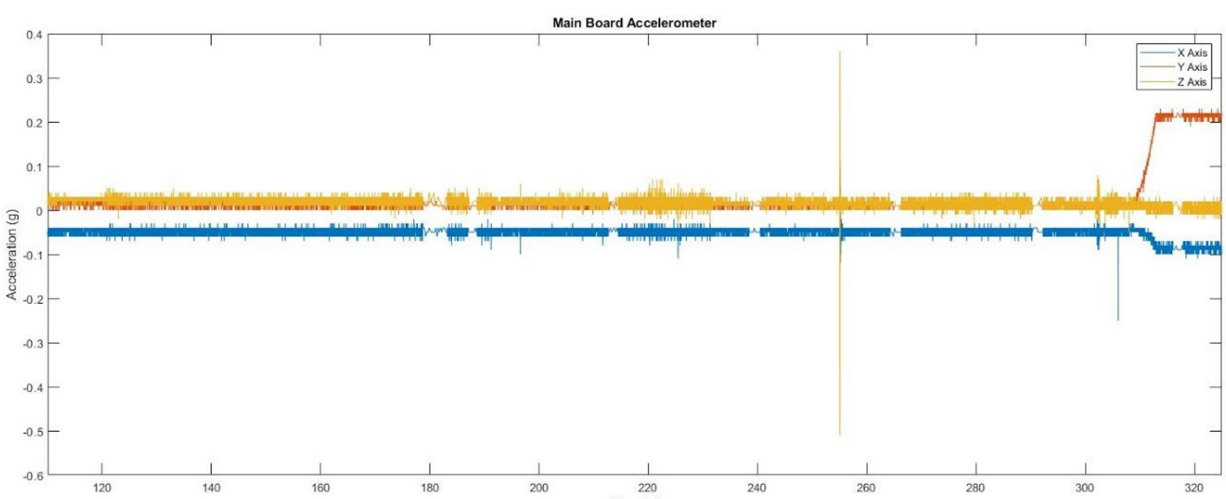

Figure 19: Accelerometer Data of Rocket Mounted IMU Flight

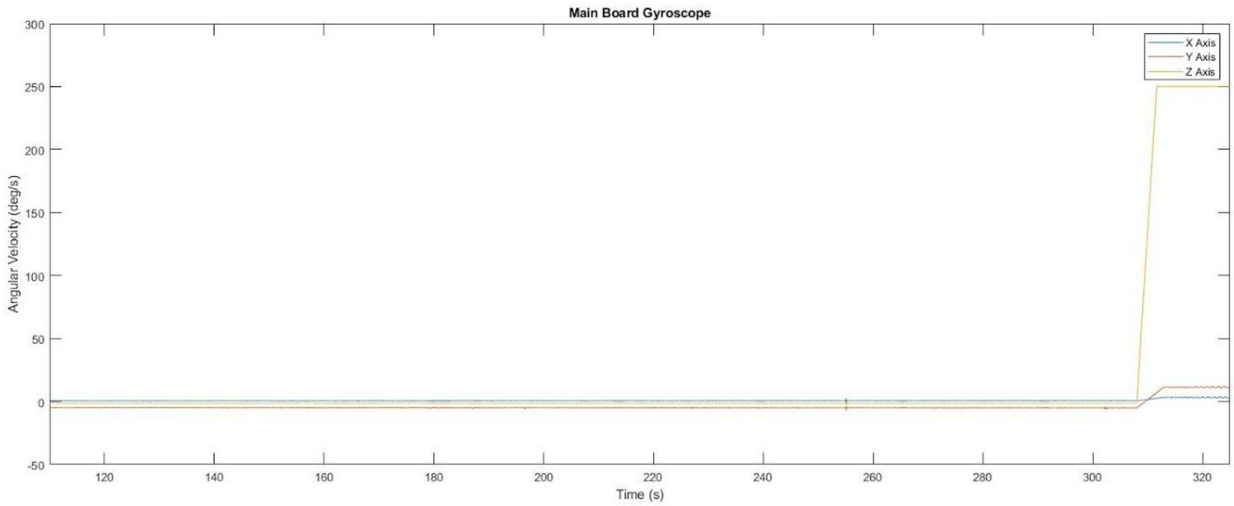

Figure 20: Gyroscope Data of Rocket Mounted IMU Flight

Figure 20 shows a plot of the gyroscope data of the IMU mounted inside the electronics housing. This plot as well shows nothing unexpected. The increase of angular velocity about the z axis towards the end of the plot correlates to ACS spin up of the rocket for reentry.

Power to the payload occurred approximately 180s before launch. Plots of the end effector data in Figures 21 and 22 begin at -180 which corresponds to T-180. This happens due to the previous software bug previously mentioned in the full mission sim.

Accelerometer data in Figure 21 shows the period of inactivity while the rocket is sitting idle on the pad. Then at T-0 launch can be seen in the data. The accels only had a measurement range of +/-2g and are oversaturated while the rocket is accelerating. After the rocket has finished accelerating a period of zero g is recorded indicating the payload is in a microgravity environment. At approximately T+121s the last of the end effector data is received and connection to the end effector is lost for the remainder of the mission. Figure 22 shows the end effector gyroscope data which provides the same information.

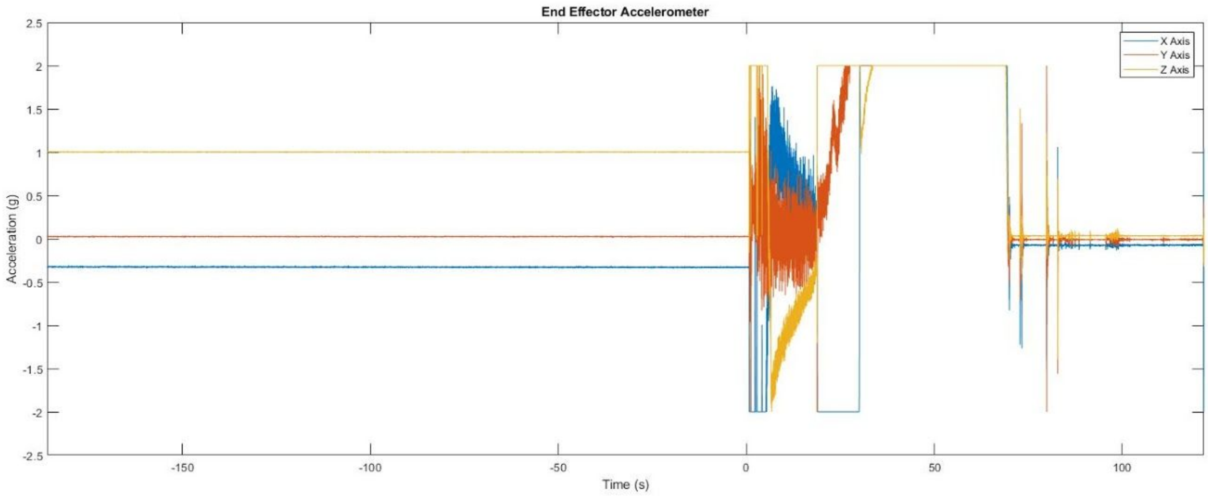

Figure 21: Accelerometer Data of End-Effector IMU Flight

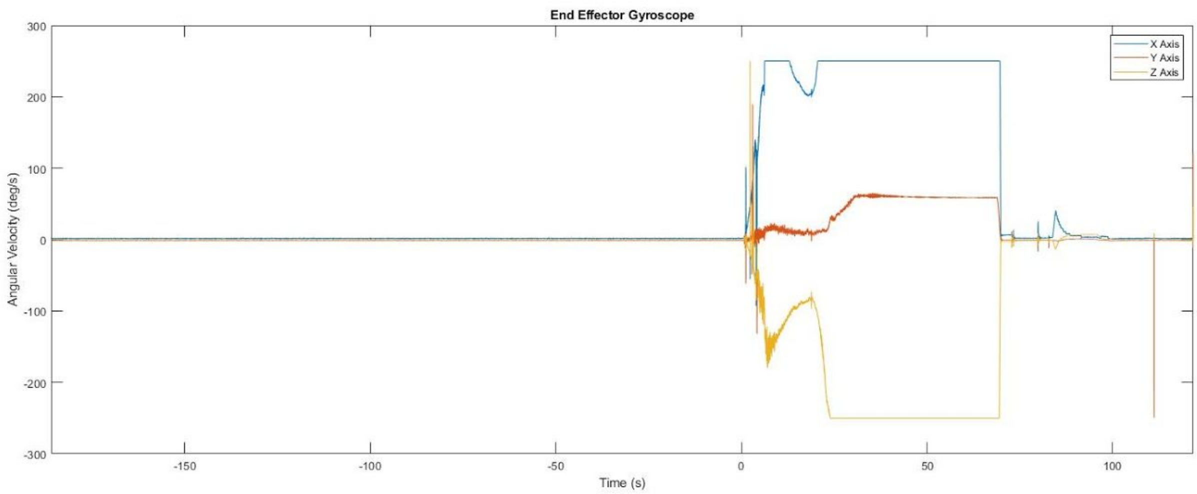

Figure 22: Gyroscope Data of End-Effector IMU Flight

The failure to record any more data throughout the mission is believed to be caused by a disconnection of either the signal, power, or ground wires to the end of the boom. Since the failure occurred at the time the motor begins turning the spindle it is likely that either the wires in the spindle or the connections inside the slip ring itself became damaged during launch then failed completely when the spindle began to turn. This implies that one of the three connections (PWR, GND, TX) disconnected as the motor began to deploy. Since the disconnect occured at this point and not during launch it is probable that a connection inside the spindle or the slip ring itself was damaged during launch and completely failed once the slip ring or spindle began to turn.

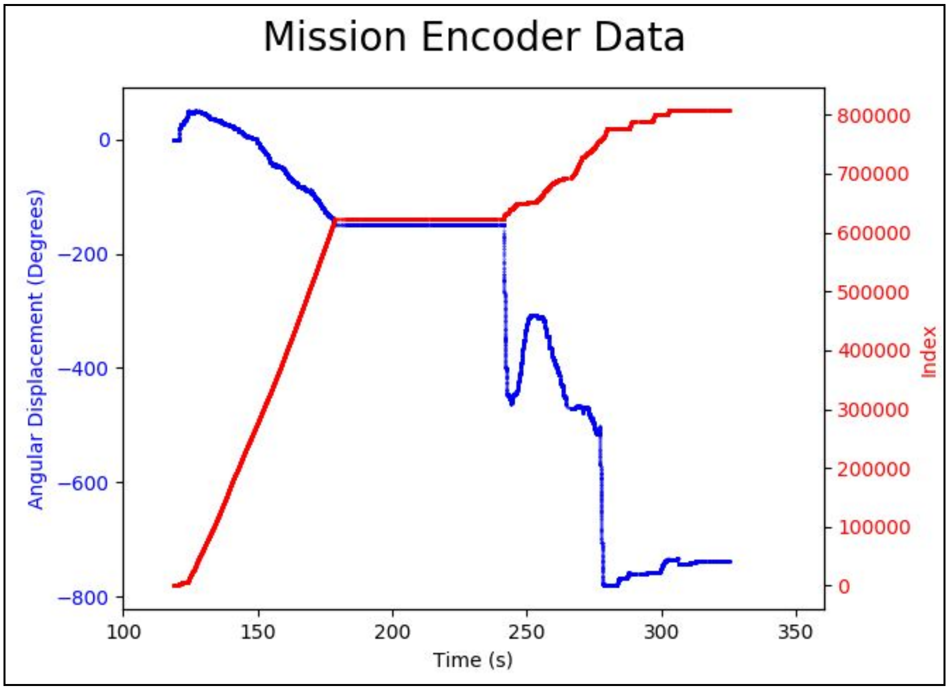

Figure 23: Motor Encoder Data Flight

Figure 23 of the motor encoder data shows a behavior far different than the expected plot from the full mission sim. Angular displacement shows an erratic and slow change over the deployment and retraction phases of the mission. While dimensions cannot be assigned to the index data, the behaviour of index data is similar to the full mission simulation with a constant speed deployment and dwell at the proper time and duration. It is believed that the off the shelf encoder used was not prepared or built for use in a space environment and seververily malfunctioned during the mission. Since both index and angular displacement both measure the turning of the motor shaft there is no way that the index readings could have a near constant linear slope while angular displacement could have such erratic changes.

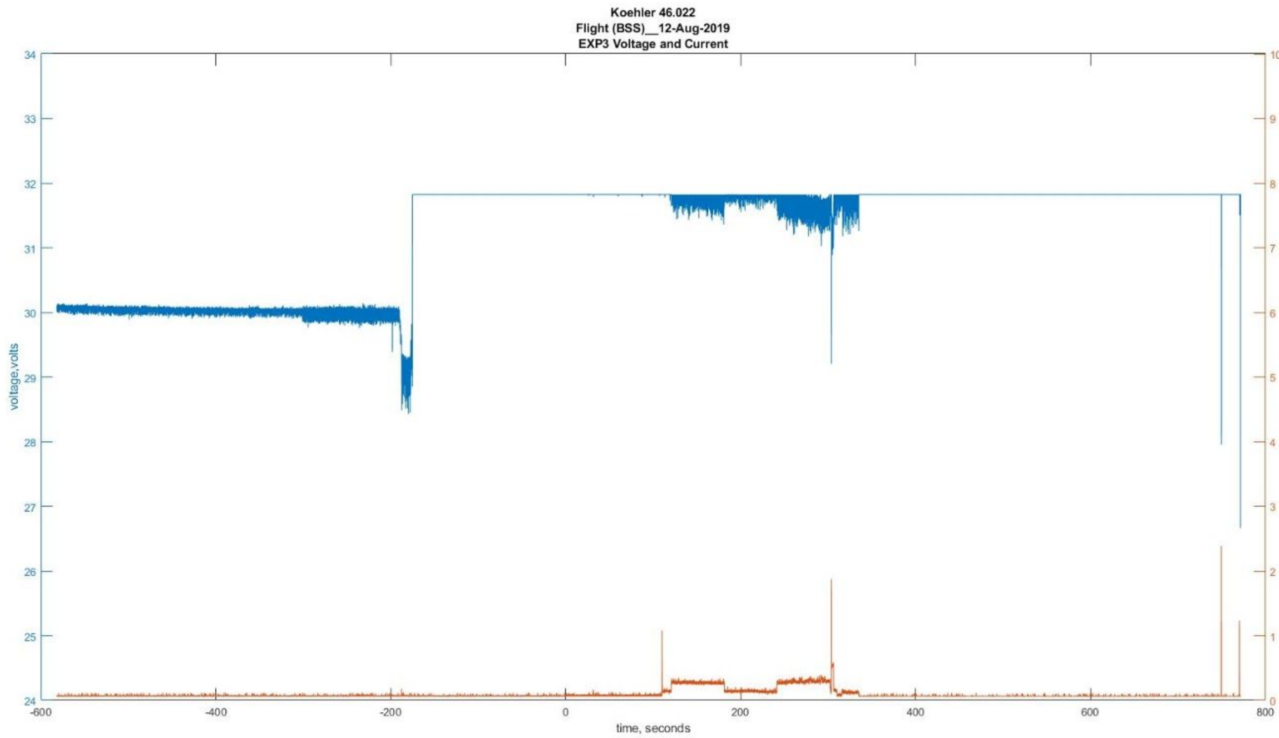

Figure 24: Voltage and Current Plot

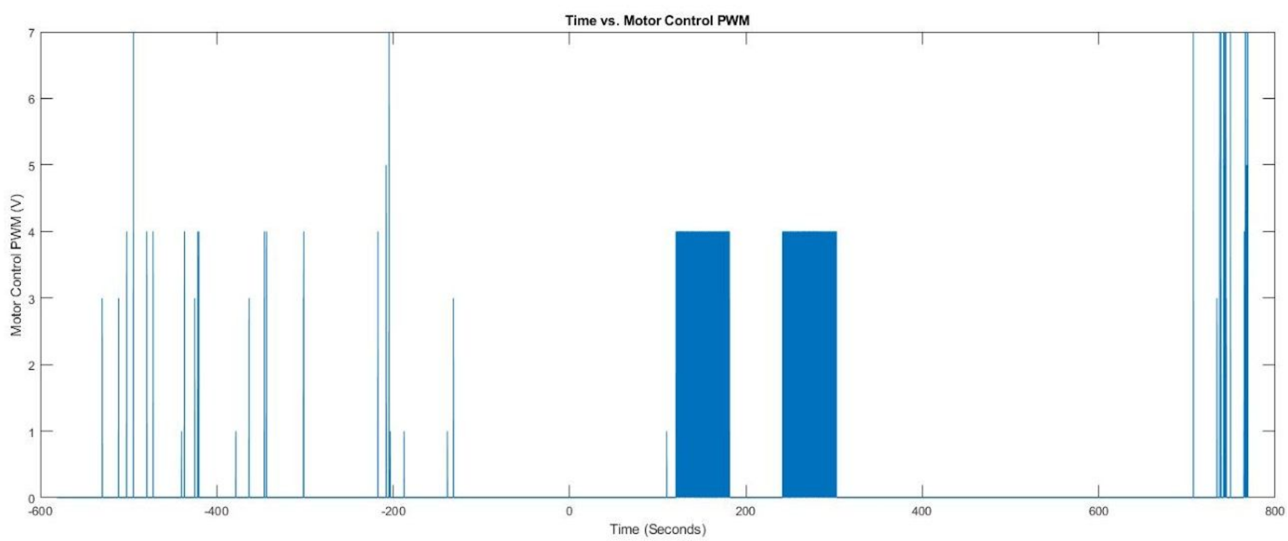

Figure 25: Motor Control Voltage

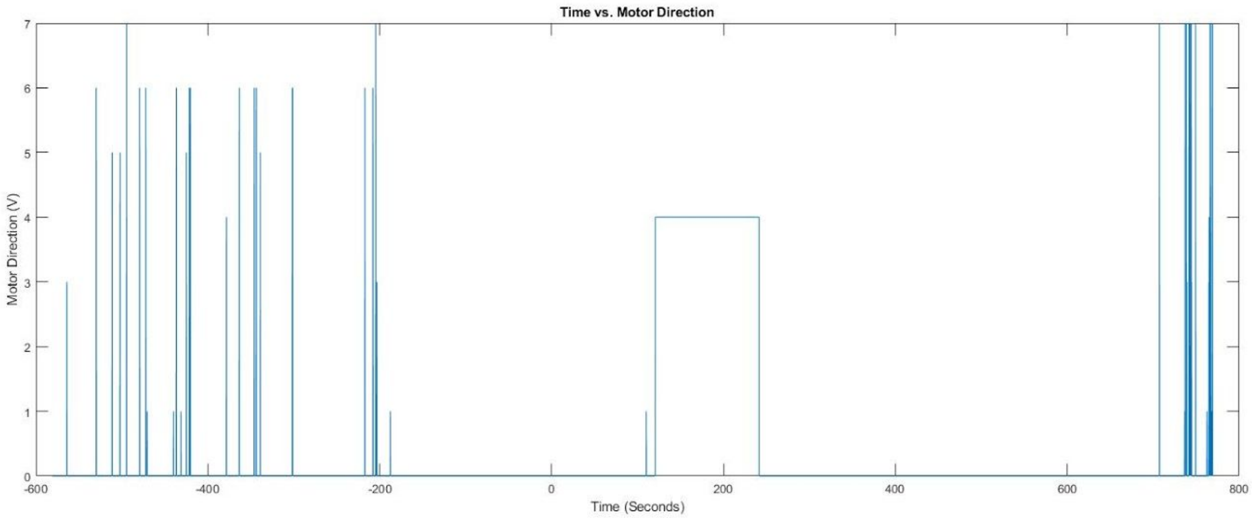

Figure 26: Motor Directional Voltage

Figure 24 provided from Wallops is a plot of the voltage and current used by the payload over the duration of the mission. Between T+110s and T+300s a current draw profile is seen that matches the current drawn by the motor to deploy and retract the boom. Also, near T+300s a large spike in current can be seen which is characteristic of the current taken by the linear actuator to close the door as expected.

The plot in Figure 25 is analog telemetry data of the signal used to control the motor's deployment and speed. The motor uses the frequency of a square wave to determine how fast to turn and when to start. This square wave is seen as expected for deployment at T+120s and retraction at T+240s. Figure 26 shows telemetry voltage data of the signal used to control the direction of the motor. The signal is set high at T+120 to indicate to turn in the deployment direction then at T+240 it is set low to turn and retract the boom.

From the plots of the encoder, voltage and current, and telemetry signals there is evidence to suggest that the motor did turn and deploy the boom. However, it is still not the data needed to definitively prove deployment or characterize the dynamics of deployment. So we do not meet the minimum success criteria with the data recovered from the experiment.

After the payload was returned to the university the team conducted a partial disassembly of the deployer. After removing the reentry shields the end effector and boom had little to no damage other than from sea water. The boom was still tightly rolled around the spindle with no gaps. If blossoming had occurred the kapton tape would prevent the boom from rolling up uniformly on the spindle. If the motor did turn as expected there is no evidence of blossoming which implies the boom could have deployed.

7.0 Conclusions

Unfortunately, there was no video evidence that the boom was fully extended and retracted; however, the combination of no mechanical malfunctions being identified post recovery and the patterns in the NSROC power signal data suggest that the SHEARLESS boom deployed successfully. Additionally, from the data recovered on the SD cards, it was verified that all of the accelerometers, gyroscopes, and temperature sensors collected and saved data successfully. The GoPro cameras did not turn on and because of that there was no meaningful data for Dr. Fernandez's research. He couldn't use the IMU data saved onto the SD cards because of a timing issue in the process. To be able to use the data, both IMU's needed to be working simultaneously. That way, post flight, someone could take the difference in readings between the IMU's to determine position, velocity and acceleration of the boom. Because the IMU's did not work simultaneously, the only data saved and recovered was that of the rocket, which isn't helpful for Dr. Fernandez's research.

Further discussing the IMU issue, there was one IMU (located inside the electronics housing), it was supposed to collect and save data from launch until the end of the mission. It stopped collecting data as soon as the motor starting deploying. IMU 2 (located on the end of the boom) started collecting data when the motor started deploying to the end of the mission, which was correct. The success of the mission depended on both IMU's collecting data simultaneously allowing for post processing to see the difference between the two measurements. Because this didn't happen, no meaningful data or conclusions could have been drawn for Dr. Fernandez.

This experience was an invaluable and unique to the undergraduate students at UNL who do not get the opportunity to work on aerospace technologies and developing hardware that does get launched into space. Students on UNL RockSat were able to apply their coursework on a challenging project and advanced their learning that can only come from completing a challenge like this.

Thank you to our partners at NASA Langley, Dr. Juan Fernandez, Matt Mahlin, Justin Green and to our Faculty advisor Karen Stelling for providing the support and guidance throughout the last several years of this project and the previous one.

8.0 Potential Follow-on Work

In the future, it would be better to increase the deployment distance. The current setup deploys to 4 times the footprint of the stowed payload. In the future, the goal is to continually increase this as to allow for decreased possibility of rocket interference with the recorded research data. For instance, collecting magnetometer data further away from the rocket will give much more accurate readings.

One of the main goals of this boom is to improve deployable capabilities for other science objectives. For future work the size of the deployer and related hardware should made even smaller so that more science could be incorporated in a suborbital launch. Also making the design should be made more modular so that it can be flexible and easily modified to achieve whatever mission it could support in the future.

Future flights will benefit from this technology because it is a basic building block which will help improve data collection capabilities for varying research instruments.

9.0 Benefits to the Scientific Community

An easily integrated mechanism to deploy and retract instruments onboard sounding rockets during suborbital experiment missions is needed. The need for a retractable boom was identified by the sounding rockets program office at NASA Wallops Flight Facility and was reinforced by engineers at NASA Langley Research Center, where they had a desire for it to be used in conjunction with collapsible solar panel arrays. Historically, numerous booms have been used for instrument deployment, but the ability to re-stow the boom and attached devices has been limited to specialized booms too heavy and slow for suborbital use. The benefits gained by re-stowing deployed devices include:

- cost savings due to the recovery of otherwise unretrievable hardware;
- the ability to directly gather and store data; and
- the opportunity to retrieve and evaluate an instrument or system exposed to the microgravity environment.

Deployment mechanisms used in previous NASA missions fall into two categories: 1) collapsible structures and 2) tape springs. Collapsible structures consist of longerons connected to interlocking joints by cables. They start in the collapsed configuration and, as they are rotated, the longerons straighten and lock into the joints creating a rigid structure. The truss-like structures differ based on longeron-joint pattern and driving mechanism; however, the main premise is the same. Examples of collapsible structures include: the Folding Articulated Square Truss (FAST) currently being used onboard the International Space Station (ISS) to deploy solar panels [1]; the AstroMast consisting of fiberglass longerons that rotate and lock into a triangle pattern to deploy a 47-ft flexible solar panel array on the MILSTAR satellite [2]; the X-Beam Boom, made of graphite fiber longerons and aluminum connection joints, designed to deploy antennas and thrust modules from the ISS [3]. The major drawbacks of collapsible structures are their kinematic complexity and their manufacturing expense. These drawbacks are exacerbated when scaling the structures down to the small design envelope of a sounding rocket payload. Tape springs, which comprise the second category, can be bistable or multistable booms made of metal or composite material. The first stable configuration is the stored position wrapped around a spindle. As a motor turns the spindle the tape springs deploy into the second stable configuration. Many variations of tape springs in varying sizes and cross sectional shape currently exist. One example is the Storable Tubular Extendable Member (STEM) Boom [4]. Another example is the SHEAth-based Rollable LEnticular-Shape and low-Stiction (SHEARLESS) boom, developed by Dr. Juan Fernandez at NASA Langley Research Center, which consists of two strips of carbon fiber composite in a plastic sleeve [5]. Tape springs have been shown to be reliable in past space missions and handle axial loading well. Their physical size and weight make them a desirable deployment method for use onboard a sounding rocket.

Development of the SHEARLESS boom also has applications outside of sub-orbital payloads. The prevalence of CubeSat and SmallSat platforms in NASA, universities, and commercial companies could benefit with the use of the SHEARLESS boom and the deployer developed at UNL. This deployment mechanism could be modified for quick deploying solar panels, retractable antenna, sample collection and retrieval, and any other applications that require a fast mechanism that can be deployed and retracted multiple times.

10.0 Lessons Learned

With the foresight after launch there are several changes that could have been made to reduce the possibility of critical failure and should be kept in mind for future missions. The end effector electronics had the capability for more redundancy. Only 3 out of the 10 connections were used throughout the boom. In the future redundant PWR, GND, and TX lines could be connected to prevent a total failure from just one of those becoming disconnected. Also a 2nd backup sensor and microcontroller could also be attached and wired. The circuitry for the camera inhibit could have been made more robust from physical failure. A second control microcontroller could be added for better reliability and redundancy. The microcontroller could read accelerometer data to determine if the actual launch had occurred and triggered the cameras off that. Future motor encoders could be selected specifically made for space. Or the motor and encoder should be tested in vacuum before being used.

Things that weren't directly related to the team's success criteria that could have been changed are discussed next. The teensy brand of microcontrollers should be used from the start, instead of the arduino microcontrollers. The teensy's have wide community support for easy development, like Arduino, but they have the added benefit of having better specifications, like faster clock speeds, more peripherals, and smaller footprints.

The use of "rugged" SD cards specifically made to withstand seawater exposure. We would have made custom PCBs with holes to solder off-the-shelf electronic board header pins to. Soldering surface mount components on a PCB by hand with basic lab equipment is not reliable enough. Bread boarded testing electronics only gets part of the way to final electronics testing. Begin assembling final electronics (design/order PCBs, soldering, wiring) halfway through the project. Leave plenty of time to test "flight" electronics and allow for redesign in case a major change must be made.

While the team did not meet minimum success, the project was able to mature and improve from the previously launched payload from USIP. The electronics and software this year were restarted from scratch and using the lessons learned from before to exceed the capabilities of what was done on USIP. Mechanical systems were able to shorten the deployer, improve the gearing for higher speed, and accommodate 10 channels of wiring along the length of the boom.

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