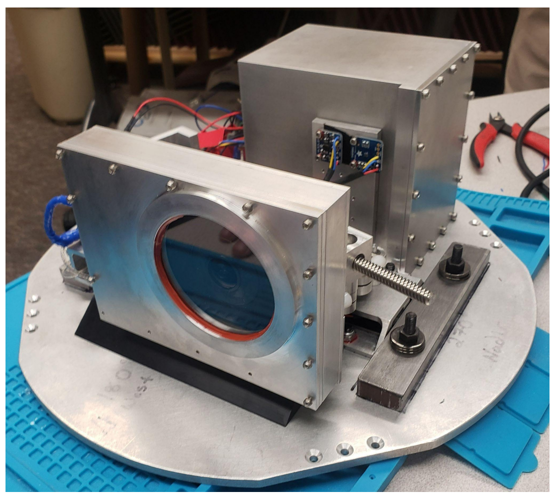
RockSat-X 2019 Final Report

VIRTUAL REALITY SPACE EXPERIENCE

Community Colleges of Colorado

V.R.S.E's primary mission was to develop a novel platform capable of external, suborbital, 360° video capture that will ultimately be used to create an immersive, virtual reality experience for NASA Wallops Flight Facility and Goddard Space Flight Center's Education and Outreach program. The secondary mission on V.R.S.E was to collect acceleration, distance, & temperature sensor data of the entire flight.



Team
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Contributing Schools
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Submittal Date
October 1, 2021

In Loving Memory of Nathan Hudson Clapp
Ad Astra

1.0 Mission Statement

The Community Colleges of Colorado (CC of CO) 2019-2021 RockSat-X team was contracted to design, build, and implement a payload capable of capturing external 360° footage of an Improved-Terrier Malamute rocket in suborbital flight. To this end, the team built VRSE (Virtual Reality Space Experience), a payload outfitted with a high definition, 360° camera, mounted on a scissor arm, which extended outside of the rocket body. The video footage will be used to create an immersive, virtual-reality experience for the purpose of education and inspiration. Our goal was to successfully transfer Standard Definition (SD) video footage from the camera to a sealed, electronics box and recover Ultra-High Definition footage (UHD) from the camera after reentry and splash down.

Our secondary goal was to collect temperature, accelerometer and distance sensor data to compare to Wallop's provided flight data to better understand our systems performance.

We learned how to design and implement a payload, with enough tolerance, that it was capable of mission success under extreme physical conditions and we then critically evaluated the integrity of our designs after launch, reentry, and splashdown. We learned how to create a sealed electronics container, using robust structural design and custom-made, fitted gaskets to protect critical data from the varying temperatures during launch and reentry. We also learned how to design and build a scissor arm mechanism with robust components, capable of functionality after exposure to extreme g's during launch, and we integrated redundancies into that design to increase successful recovery of critical data in the event of a mechanical failure.

2.0 Mission Requirements and Description

The primary mission for the CC of CO RockSat-X team was to develop a novel platform capable of external, suborbital, 360-degree video capture that will ultimately be used to create an immersive, virtual reality experience for NASA Wallops Flight Facility and Goddard Space Flight Center's Education and Outreach program. Our mission requirements were to adhere to the specific guidelines set forth in the Colorado Space Grant Consortium RockSat-X User's Guide as well as meet the contract requirements set forth by NASA to capture 360° video footage from outside the rocket body. The original project was contracted out to Red Rock's Space Grant RockSat-X program in 2019. A secondary camera that would record the arm extension and retraction was descoped due to time constraints.

The greatest design requirement imposed on this project was space availability and the speed limitations on camera extension. The Madventure 360° camera chosen at the beginning of this project was large and the camera casing needed to be as strong as possible and be able to mount to the scissor arm for extension and retraction. One of the original design concepts included a dual scissor arm (two scissor arms positioned in parallel with respect to one another) mechanism but due to height limitations this was remodeled into a single scissor arm.

The most critical design specifications that needed to be met was the transfer of the video footage from the camera to the Raspberry Pi housed in the electronics box. We wanted to guarantee the transfer of data as well as keep the seal on the electronics box water tight. To this end, we incorporated watertight D-sub's that met our wiring requirements and then modified the CAD around these components to ensure a watertight seal.

3.0 Payload Design

The final design of our payload was reached through the meticulous, iterative process of CAD design, 3D printed testing, integration of tested parts to existing parts and to the electrical system on the flatsat, and then eventually onto the payload deck. The 2019-2020 team that worked on the beginning stages of this payload left us with a repository of CAD with all of the designs they had last edited but not completely tested. That is where the 2021 team took over around February 7th 2021. The following paragraphs will only cover what the 2021 team saw as the most crucial changes that needed to be made to increase structural integrity and mobility that led to the final payload design.

The 2021 team started by looking at strengthening the way each scissor arm member was individually held together by taking the existing milled aluminum arm members, and increasing the mounting holes from 4mm to 7mm in diameter. This was to allow for a small flanged ball bearing to press fit into the hole. With the flange bearings mounted on either side of the mounting holes, we were able to ensure that we could tighten the arm members without the contact friction experienced with the previously designed method of using a clevis pin to secure the arm joints together. This addition made for a more rigid scissor arm that had less friction when moving.

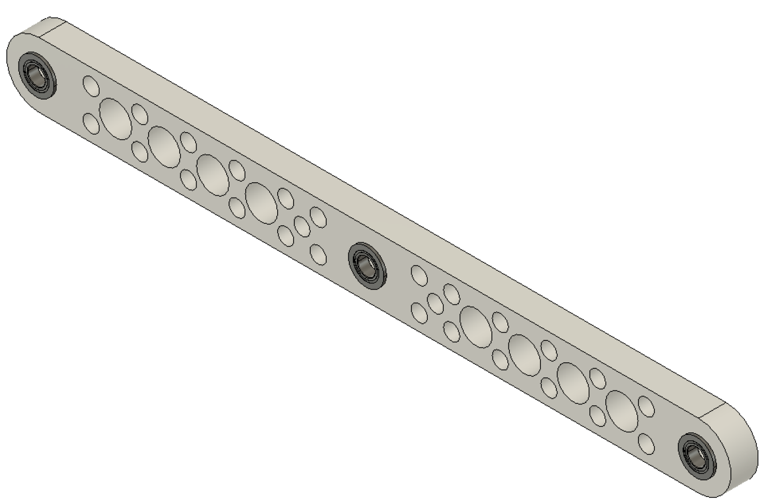


Figure 1: Scissor Arm with flange bearings installed

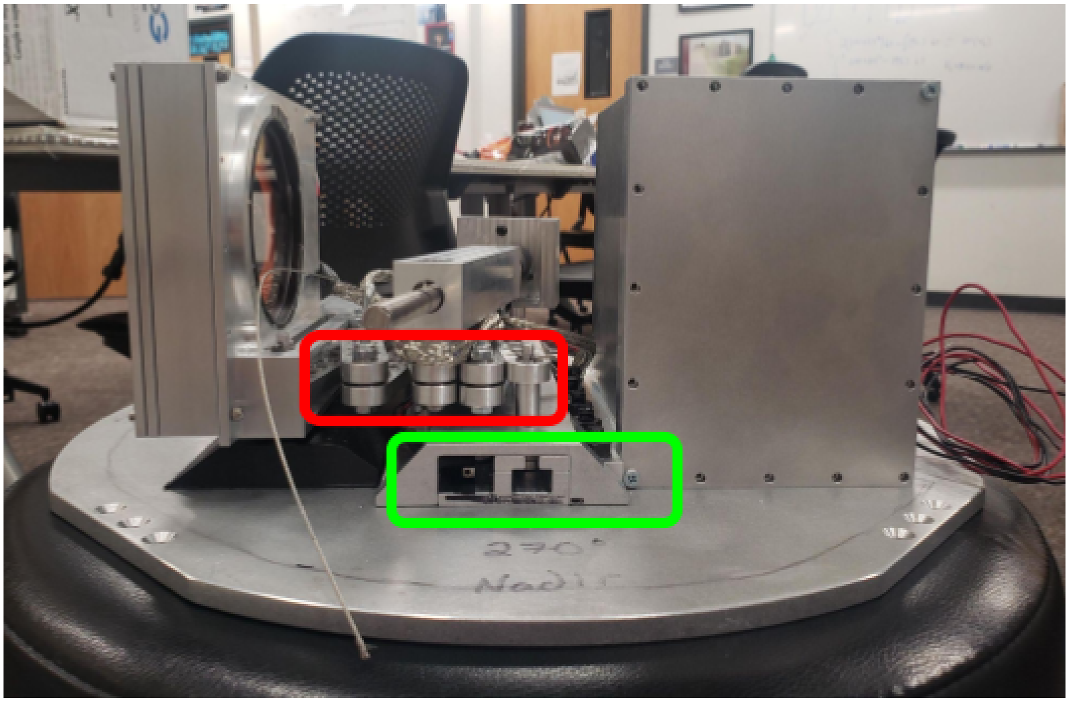


Figure 2: Side View of payload (Scissor arm spacing & Arm Base)

This design change provided the necessary clearance for the scissor arm members to not have any points of contact with each other except for the surface of the flange bearings through the full range of motion of the scissor arm as seen in **Figure 2** in the red box.

The next design change was to reduce friction between the clevis pin holding the scissor arm and what we referred to as the "Arm Base" shown in **Figure 2** in the green box. Originally the design was a clevis pin placed through the bottom of the Arm Base and going through the scissor arm and secured with a cotter pin. The friction between the two resulted in an unsteady arm extension and retraction. Instead, we designed a track that a bearing could slide in and distribute the linear motion of the clevis pin into a rotational motion, to minimize friction. This design change had the added benefit of increasing the structural integrity of the mounting point for the scissor arm. Also, by creating the "Under Arm Track" as seen in **Figure 3**, we were able to incorporate the limit switches that were the physical signals on when full extension of the scissor arm was reached and when retraction was completed so we could stop the motor at the appropriate time.

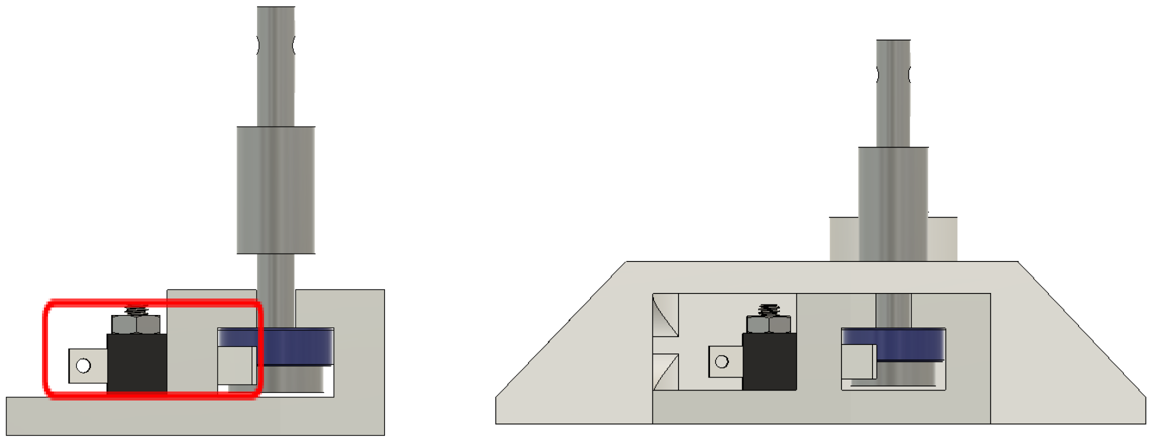


Figure 3: Under Arm Track with (Left) and without (Right) Arm Base

In the above figure you can see the bearing colored blue and the positioning of the limit switches (Red box) and where they would be depressed by the bearing. The addition of the bearing allowed the clevis pin to ultimately rotate freely during its linear path during extension and retraction.

Our third major redesigned component was the Electronics Box or “Ebox” and the system used to mount all the electronics inside the Ebox. From where we started to the final payload design, the Ebox was flipped to the opposite side of the payload, and an additional hole was added for a 44 pin waterproof D-sub. Additionally, a mounting system for all of the electronics housed in the Ebox was redesigned from a card that slid into a slot to a sleeve that had the same outer diameter as the inner diameter of the Ebox. Originally there were going to be no changes to the Ebox for the sake of time, but when we realized that the current design we had was only possible with additive manufacturing and not subtrative, we had to rethink how the electronics would be secured. Changing the design also gave us the opportunity to increase the overall volume of the inside of the Ebox. We were careful to stay within our height limits which was 5.13 inches from the baseplate and within the keepout zone limits provided for us in the RockSat-X User’s Guide (see Appendix for User’s Guide). **Figure 4** below shows the CAD design and an image of the inside of the Ebox fully integrated after launch completely intact.

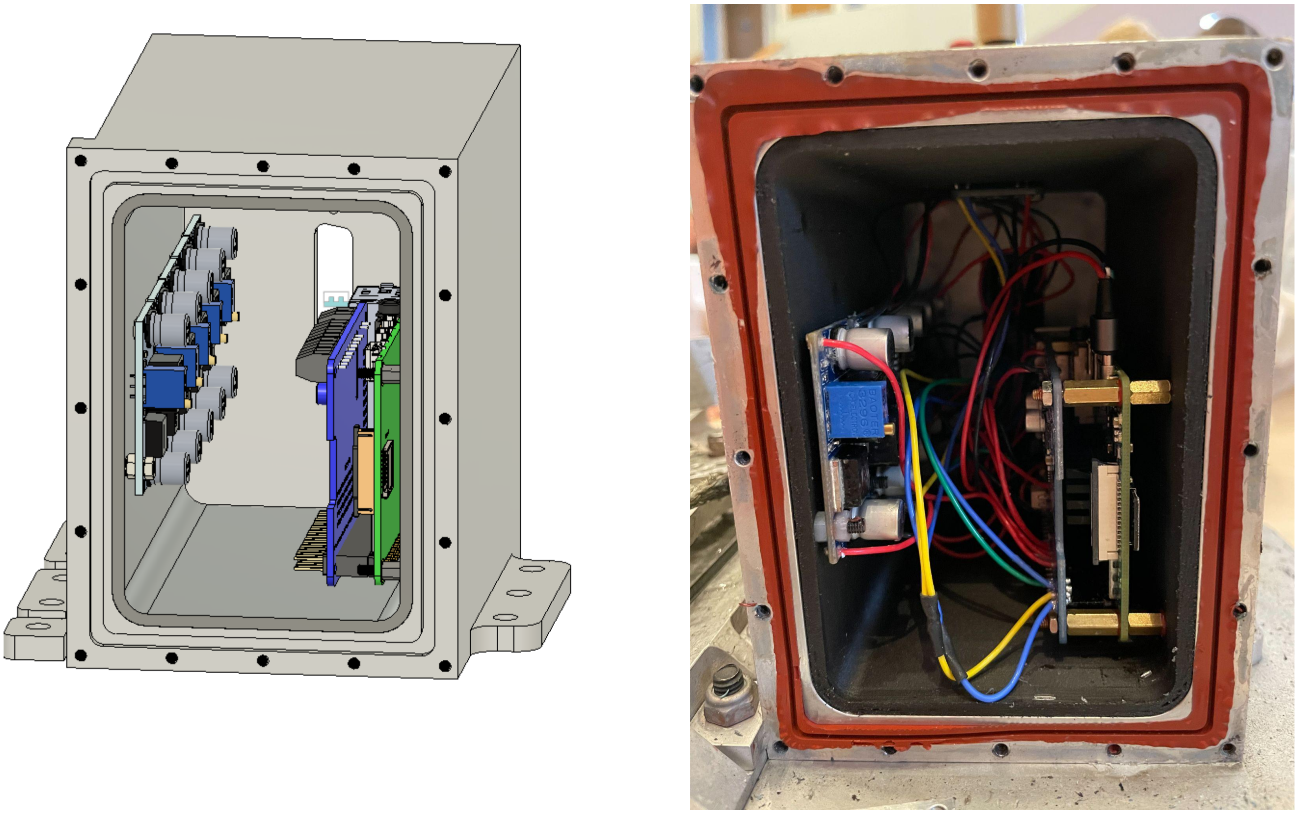
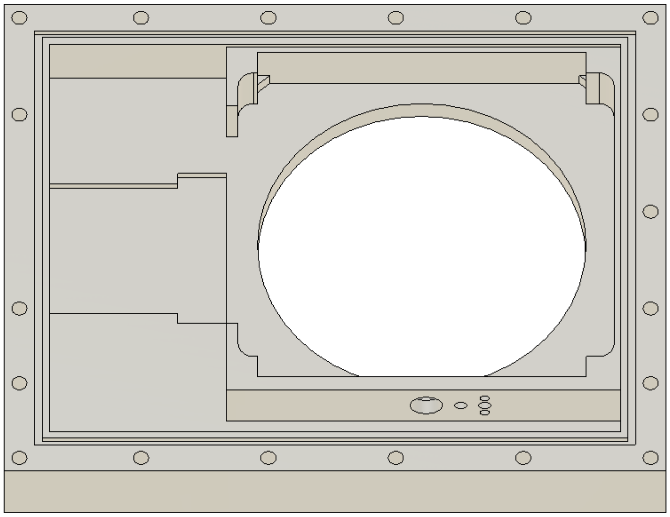


Figure 4: CAD of Ebox and Electronics Sleeve (Left) Final Integrated Design of Ebox and Electronics Sleeve Post Flight (Right)

The last subsystem of this project that was redesigned was the Camera Case. The original design allowed for the Mad-V 360° camera to rest in the case either vertically or horizontally (see Appendix for information on Mad-V 360 Camera). As it was, the camera case was not within the height restrictions so we removed the vertical camera placement option. Additionally, the vertical camera alignment did not give access to the SD card port, and the horizontal alignment was how we were able to bring the camera case within the height requirement. (See **Figure 5** below) The camera case design for structural integrity was top priority. An unsuccessful recovery of the camera would be a primary mission failure because our final design was only able to transfer the standard resolution video back to the Ebox. The UHD 3849 x 1920 video was saved locally on the camera's SD card. A 1/16” gauged steel wire rope tether was attached to the camera case and anchored to the base plate of the payload for redundancy.



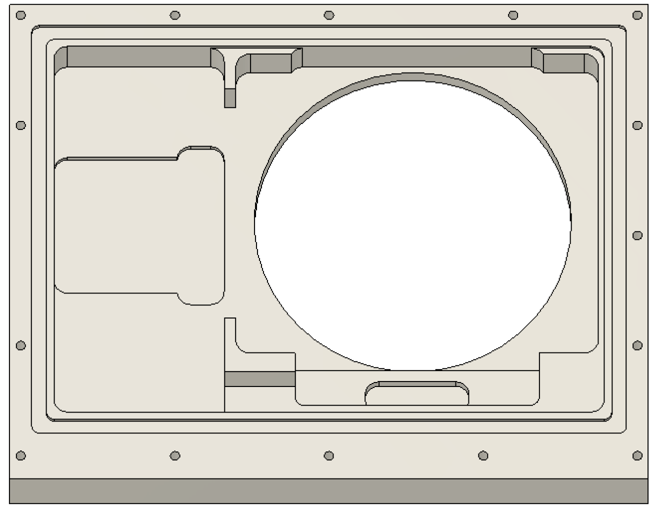


Figure 5: 2019-2020 camera case internal CAD (Left) 2021 Camera Case CAD only horizontal model (Right)

The electrical interface that was originally designed to control the camera involved removing the electronics from the selfie stick adapter. Instead of removing the electronics, the 2021 team decided to use the case that the electronics came in and incorporate that whole assembly into the inside of the camera case shown below in **Figure 6**.

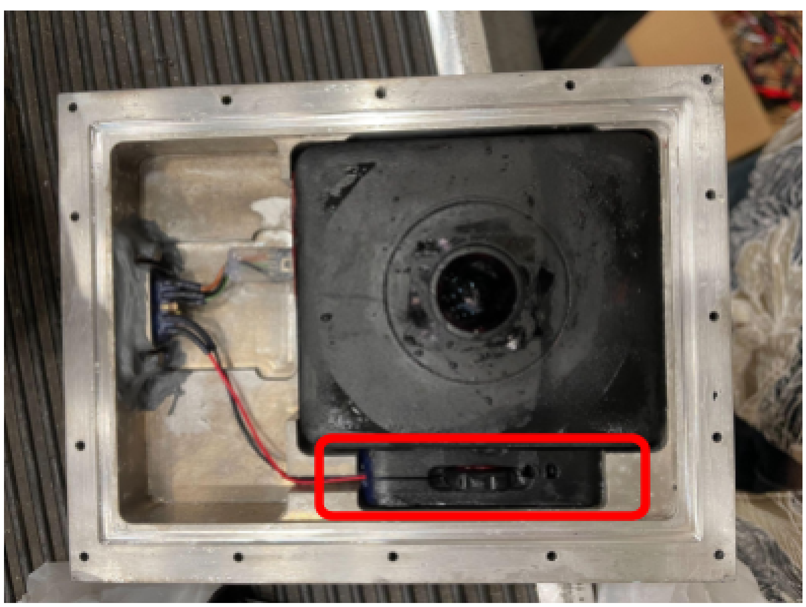


Figure 6: Camera Case internals with Selfie-Stick electronics case integrated (red box)

A basic functional block diagram can be seen in **Figure 7** below. The Raspberry Pi was the brain of our system and five buck converters were used to distribute appropriate regulated voltages to different control subsystems of the Raspberry Pi. The motor hat attached to the Pi was used to drive the motor subsystem and held the camera control circuit. All these ICs and components were housed in the aluminum milled electronics box. The DC motor would receive power when given the appropriate signal from Wallops and the limit switch would engage, cutting motor power, when the arm was fully extended. Once the next timing event was triggered the DC motor would turn on and start to retract the camera back towards the payload. When the retraction limit switch was depressed, the DC motor would again turn off. Below in **Figure 8** the detailed wiring diagram of the entire system is shown, and **Figure 9** includes our wiring harness and D-sub pinouts.

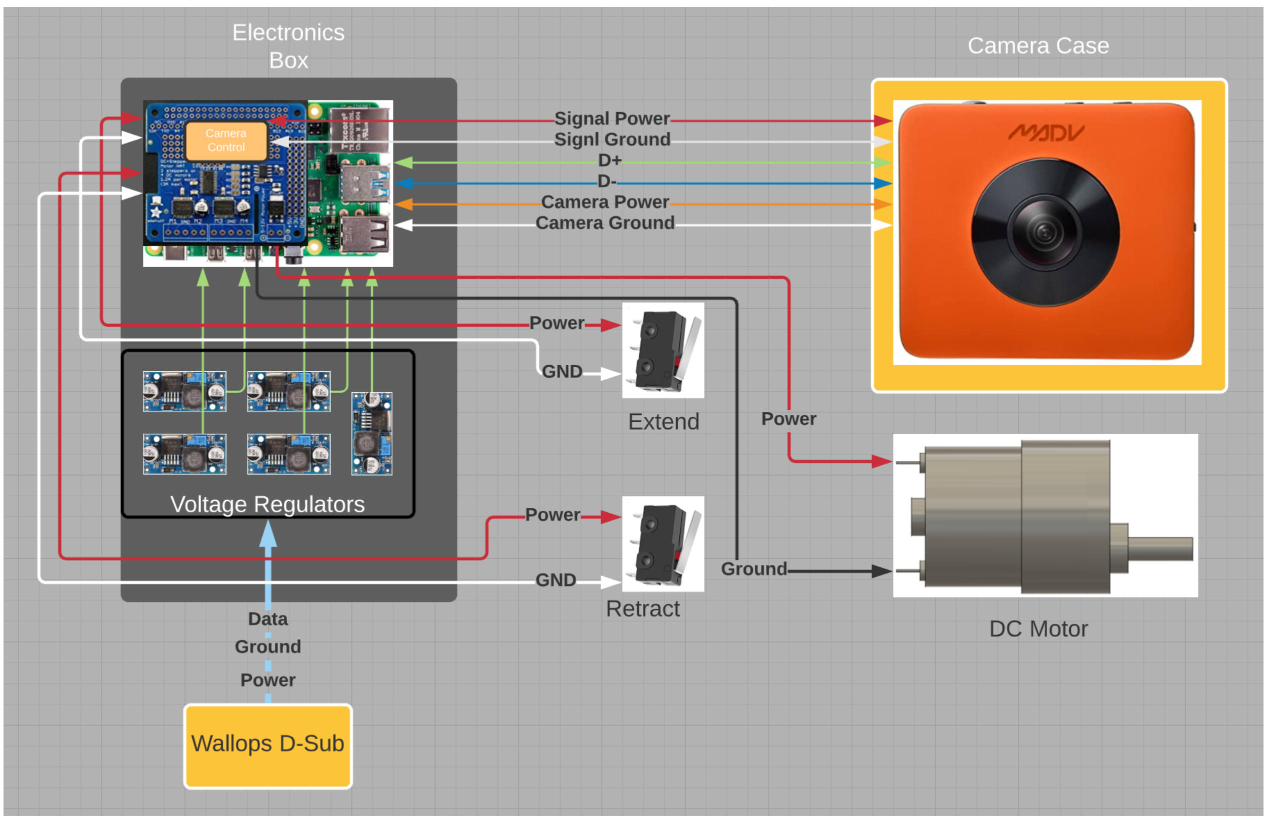


Figure 7: Basic System Block Diagram

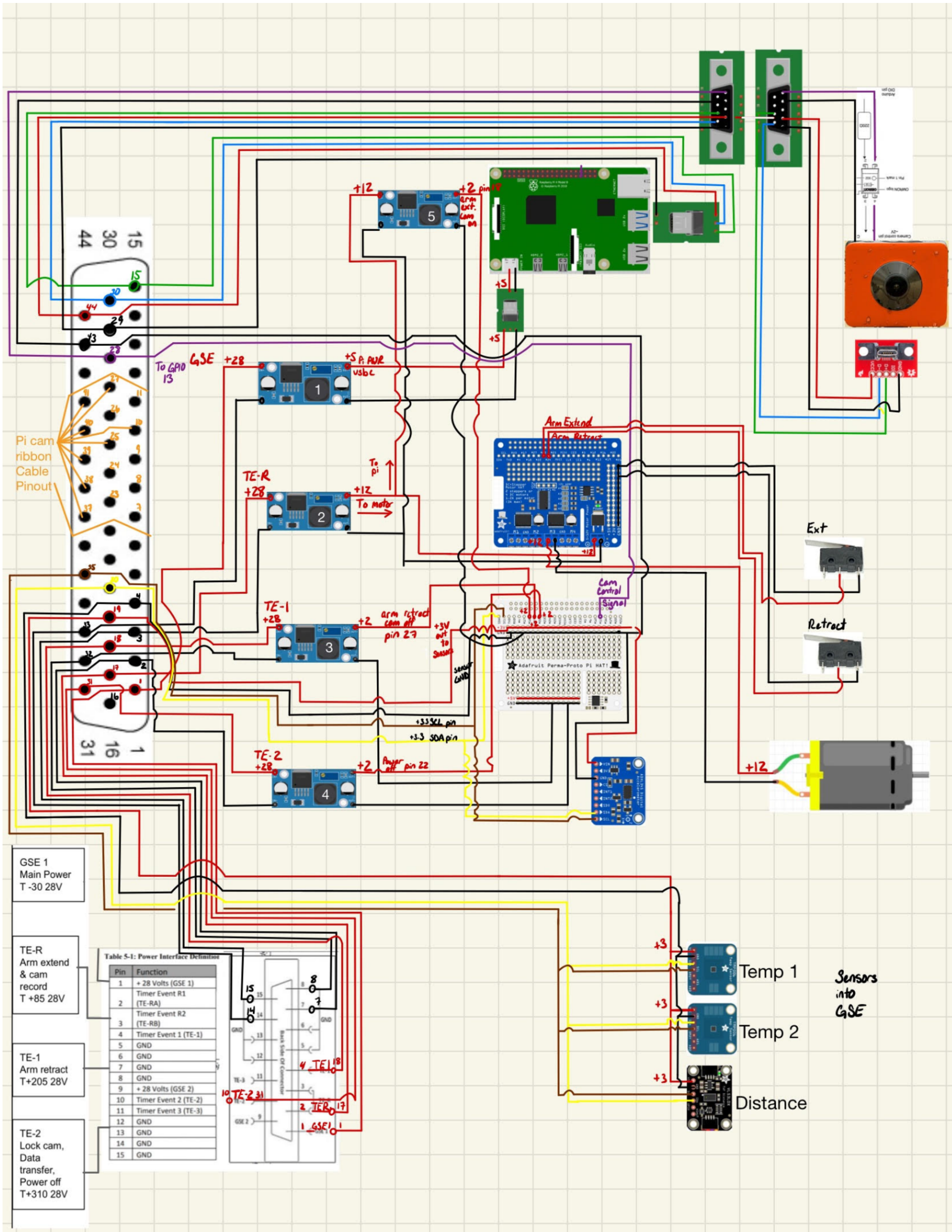


Figure 8: System Wiring Diagram

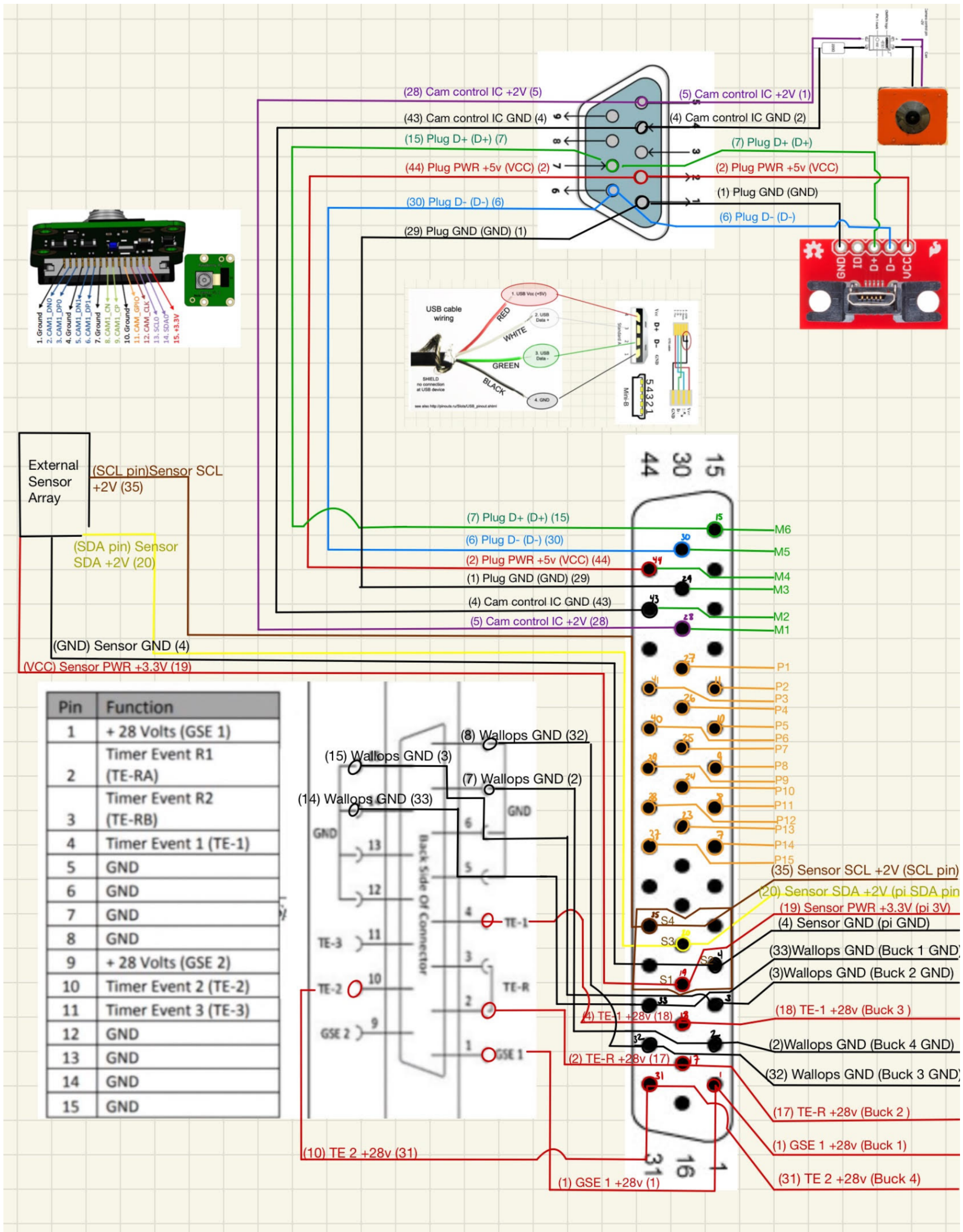


Figure 9: Detailed wiring harness guide and D-sub pinouts

4.0 Student Involvement

2021 RockSat-X Team

Name	Major	Role	Responsibilities
Andrew Bruckbauer	Cyber Security	Programming Co-Lead	Original sensor, camera, and arm control code.
Stacie Barbarick	Materials Science	Electrical Lead	Wiring and electronics integration, testing design
Cassidy Bliss	Engineering Physics	Integration & Testing Lead	Integration and testing of Electrical, Mechanical, and software systems
Caleb Christianson	Astronautical Engineering	Mechanical Advisor	Transition previous team's CAD to current team's mechanical Lead.
Anton Vandenberge	Electrical & Computer Engineering	Mechanical Lead	Redesign and Finalize CAD for flight, Electrical integration
Konstantin Zaremski	Computer Science	Programming Co-Lead	Flight ready overhaul and optimization of existing codebase

2019 - 2020 RockSat-X Team

Name	Major	Role	Responsibilities
Andrew Bruckbauer	Cyber Security	Programming	Sensor, camera, and arm control code.
Caleb Christenson	Aerospace Engineering	Electrical/Mechanical Lead	Electrical System Design/CAD Design
Nathan Clapp	Computer Science	Programming Lead	Software creation and implementation
Mac Grove	Cyber Security	Programming	Software creation and implementation

Tiffany Lovett	Computer Science	Programming/Electrical/Bio Team Co-Lead	Censor Software/Circuit Design
Faatasina Luifau	Mechanical Engineering	Mechanical	Mechanical team / CAD
Spencer Madison	Business	Assistant Project Manager	Organization / schedule management
Segev Morgan	Computer Science	Mechanical	CAD design
Onterrio Morris	Computer Science	Programming	Software creation and implementation
Santana Padilla	Chemistry	Boi-Team Co-Lead	Research/Design of Secondary Bio-Experiment
Cid Quezada	Mechanical Engineering	Mechanical	CAD design
Marieke Spiegleman	Astronautical Engineering	Project Manager	Project manager / electrical team
Jared Stroud	General Engineering	Mechanical	Preliminary design
Shannon Walters-Dorchak	Geophysics & Planetary Sciences	Assistant Project Manager	Initial CAD work / Budget and Inventory management

5.0 Testing Results

Our payload testing was rigorous and iterative as each new component was integrated as a prototype, tested, refined, and eventually integrated into subsystems. Subsystems were then tested mechanically, refined, and eventually wired and tested completely. Once subsystems were functioning consistently with a power supply, they were then tested with our software. . As each subsystem became fully functional, we began integrating them together, refining their dynamics and integration points as needed. We focused on four major categories of testing: our preliminary wiring and components on our flatsat, the mechanical arm system , the integrity of the electronics box and camera case, and camera testing and integration.

Flatsat

We began with a flatsat for testing electrical systems from the ground up.t..We were able to keep systems organized until they were completed, and this set up made for easy disconnection and modular integration. We tested and calibrated components individually, troubleshooting faulty connections or hardware when required. Once components were functioning properly, we tested subsystems, following the same refining method until successful. We were able to isolate and identify our most common issue, which was wiring connections, by using quick-connections between components. Furthermore, this was an ideal setup when we had a more serious failure, such as a Raspberry Pi, and were able to replace it without disruption to the rest of the system. Mechanical systems were not added to the flatsat until both the mechanical subsystem and the electrical system were functioning independently and consistently. As each subsystem was integrated to the flatsat, we would test first electronically and then use software to control the system. The flatsat gave us insight on the weaknesses within our subsystems, as well as a clear map of our wiring systems. With this design setup, we could easily use a computer monitor to run and debug our Raspberry Pi code, and were eventually able to remotely access files and code, as seen in **Figure 10** below.

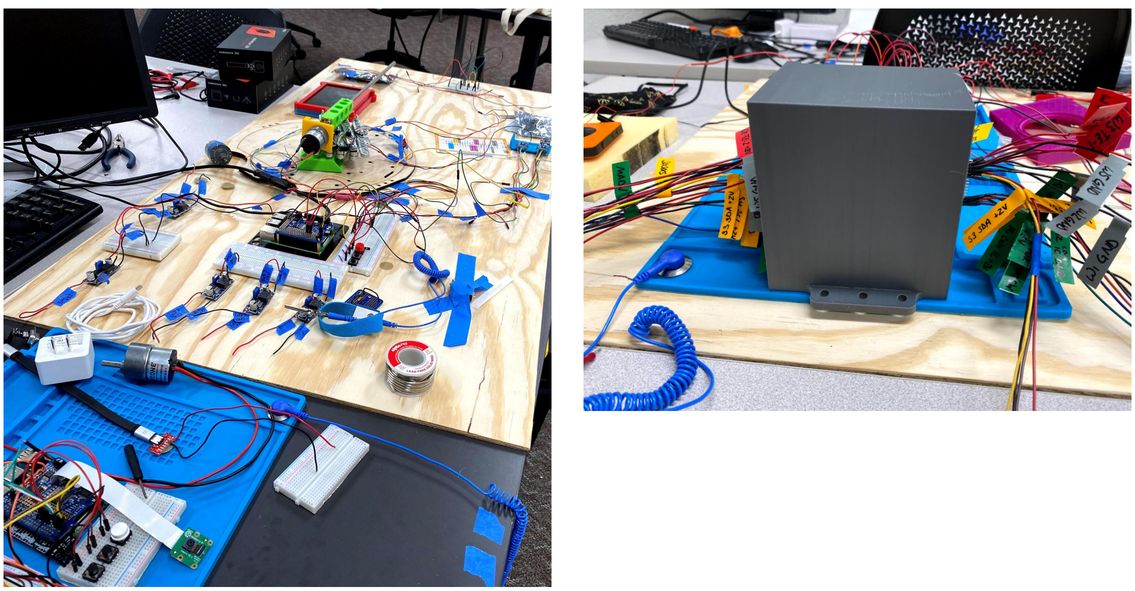


Figure 10 : Flatsat used for prototype wiring, component, and subsystem integration.

Mechanical Arm System

Our first priority was correcting hole sizes in the arms, which had been previously manufactured, to fit standardized hardware for mounting points. We tested multiple connection hardware options for the scissor arm stability and mobility. We settled on a six-part joint assembly of each "non-mounting" joint that provided a rigid and mobile movement as the scissor arm would extend and retract. We 3D printed versions of components and tested them mechanically before we sent finalized designs to be milled. Many changes were made as some joints required more support than others. The linear rod guide, which connected the motor to the scissor arm, ended up being difficult to support and connect due to the size of our joints. We found that a larger-surface connecting point was key and made a custom-length bolt to resolve these issues. Later, we would use testing of our min and max extension to cut the actuator rod at the appropriate length. The most difficult joints to refine were the end joints, where the scissor arm would attach to both the arm base-plate and the camera case. After much testing, and collaboration with the mechanical team, each end joint had custom parts created to support and secure the vital connections. The joints that would move along a track could not be tightened down as friction would increase, causing our motor to struggle and the track to be damaged. We therefore moved to a custom clevis and cotter-pin system at these points, adding custom bushings to take the brunt of any damage caused by weight-bearing, rather than the track. The limit switches that would end up controlling our signals for the camera, were added late in our design. As a consequence, the positioning of the limit switches within our arm base plate was a difficult process. As our deadline approached, we sent off the design for our arm base plate and track system before enough testing of the limit switches had been done. Our slot for one of the limit switches ended up being about 2 milimeters off, and physical adaptations to the limit switch itself were required to make the system perform properly. We determined the weakest points in the arm system and ran dynamic calculations on the forces these areas would experience during launch, and found that our clevis pins would fail and deform without added support, shown in **Figure 11** below. We decided to integrate a delrin block attached to the deck that the camera assembly rested on during launch. The delrin was designed and milled to the shape of a ramp to allow the camera case to slide back up the ramp during retraction.

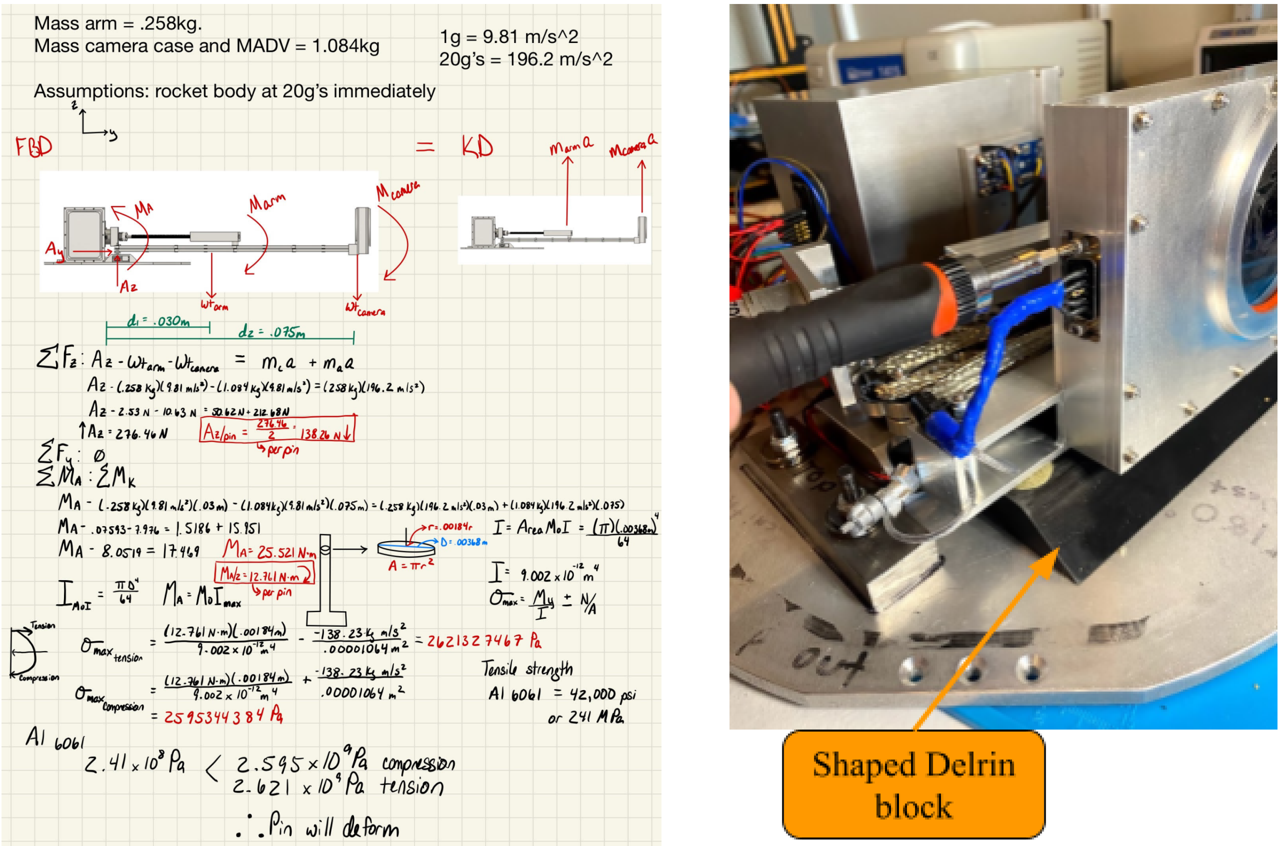


Figure 11 : Abbreviated calculations showing pin failure (left) and added a delrin support to negate the issue (right).

Running the wiring harness down the scissor arm to the camera was more difficult than expected upon testing. We had holes available to mount to on the arm, however, when the harness was mounted to these points, the harness would obstruct the scissor arm's ability to close completely. In order to correct this, conduit clamps were installed on the corner joints, allowing the harness to pass around the joint to the next mount point, allowing clearance for the scissor arm retraction. The downfall to this solution was the height requirements of those joints increased, and new hardware would need to be purchased. The linear rod actuator attached from the motor to near the center of the arm assembly on the outside joint. This became an issue when we realized that there was slack in the scissor arm, from where the rod guide attached to the camera case. Therefore, the arm, under certain conditions, would not remain in its resting position or within the required bounds of our base plate. We conceptualized many options, however, we came to this realization close to our deadline and integrating a new electrical device of any kind would be very difficult and disruptive to our current system. Additionally, there was little space left on our payload to fit a new device that would inhibit the slack in the arm system until we intended for it to extend. Our solution was simple. We used velcro to inhibit our camera case where it rested on the delrin ramp. Testing allowed us to determine how much velcro was enough to hold the weight of the camera case and the slack in the arm, but little enough for the motor to overcome when extending. We used force meters and repeated directional testing to verify the extension end-location and viability. We took an average of 20 trials to calculate the average velocity for extension. The average velocity of extension was 0.6145 in/s, and the average velocity of the retraction was 0.5523 in/s, both well within the 1 in/s maximum velocity set by the user's guide.

Watertight Integrity

Since we were recording high definition, 360° video, we were not able to transfer that large of a data file through our wiring harness back to the safety of our electronics box.Therefore, it was imperative that our camera case was water tight. We conducted multiple experiments to ensure water resistance with different types of gasket materials. We initially tested our 3D printed electronics box with different cut-to-fit gaskets and pourable gasket materials with poor results (see **Figure 12, left**). We then created a mold of the electronics box with hopes of pouring gasket material into the mold, but the weight of the aluminum Ebox limited the molds we could accurately make. Unfortunately many waterproof, high temperature gaskets were not removable and we needed to be able to open and close our camera case and Ebox without ruining the seals.

After several unsuccessful attempts, we finally decided on a product called Mold Max® 60 Higher Heat Resistant Silicone by Smooth On. (see Appendix for Mold Max) It was developed for high-heat resistance applications and can withstand up to 560°F / 294°C. It featured a low mixed viscosity and the cured rubber exhibited very low linear shrinkage. There were two parts A & B which were mixed 100A:3B by weight and then degassed in a vacuum chamber at 25psi for three minutes. The pot life is 40 minutes which allowed us to scrape the mixture into our aluminum pieces and cure in 24 hours to a relatively hard Shore 60A so we could still remove the casing lids as seen in **Figure 12 (right)**.(see Appendix for Shore Hardness Scale)

Figure 12 : Attempted removable gasket with 3D printed ebox (left) and final selection of gasket material which was mission successful (right).

Camera Integration

We conducted myriad camera tests by taking video in varied camera case prototypes, using different site glass thicknesses and in varied lighting conditions to ensure the highest quality video was captured. In addition, we built a prototype rocket assembly (see **Figure 13** below) and attached our mechanical arm and camera. We could then gauge what would be in the camera FOV, how the camera focus adjusted to movement, and high definition performance of the camera given geographical markers.. The results of this testing were satisfactory, except for slight glare in sun-lit conditions. While conducting indoor camera testing, with low-lighting, we found that the indicator lights on the front of the camera and the orange body of the camera severely tinted the video collected while inside the case. To counteract this, we sanded and painted the camera with Rustoleum High Heat Bar-B-Que matte-black spray paint. This paint resists temperatures up to 1200°F, which would ensure that it wouldn't burn off and expose our video footage to orange color reflection, or obstruct the camera with paint chips. (see Appendix for Rustoleum Spray Paint)

Figure 13 : Outdoor testing with our rocket prototype (right) and indoor video quality testing (left).

6.0 Mission Results

CC of CO's V.R.S.E. payload flew from NASA's Mid-Atlantic Regional Spaceport on August 19, 2021. It recorded 1:57 of high-quality UHD 360° video of other experiments and the Earth around apogee. It succeeded in its preventive measures by copying a low resolution copy of the video to the Raspberry Pi. As confirmed by sensor readings and visual confirmation from the video, the arm extended fully and retracted to a point that was expected by the design limitations of the arm. Sensor data was collected through the launch until TE-2, but accelerometer data was not as useful as intended.

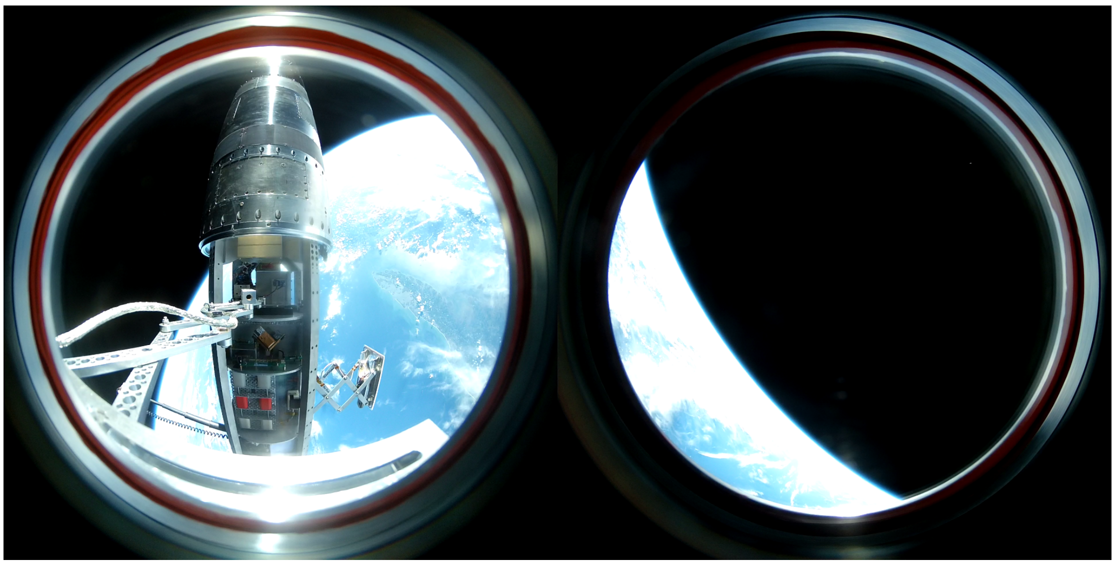


Figure 14: Still image from the high quality video at a point of full extension

Video Quality

The video delivered by our payload was unaffected by the sight glass covering the camera lens and there were no significant reflections or artifacts produced by the sunlight against the polished surface of the camera case or bezel. The camera case obstructed the outer field of view slightly, resulting in a black band around the video when stitched.

The raw video alone can not be viewed in Oculus headsets or on YouTube. It must first be stitched/projected in software to accommodate these viewers. Stitching was performed by Xaiomi's MiSphere 360 software.

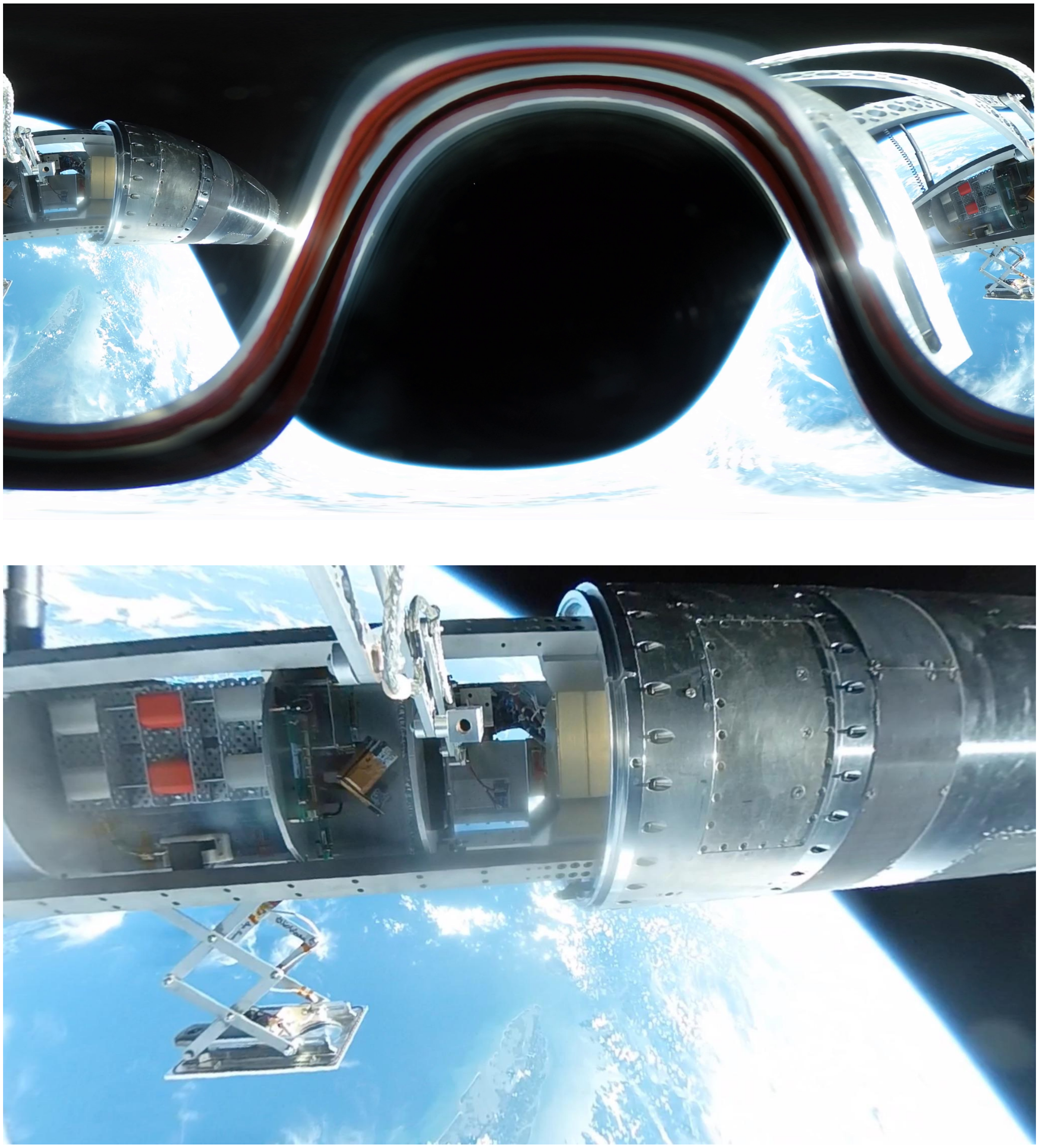


Figure 15: Previous frame stitched by Xaiomi software (above) and a different perspective of the same frame in a compatible viewer (below).

When panning the 360° video and looking at one of the edges of the camera case the continuity of the horizon line is made evident which means that the sight glass did not provide any additional distortion that would affect the stitching of the video by the standard software.

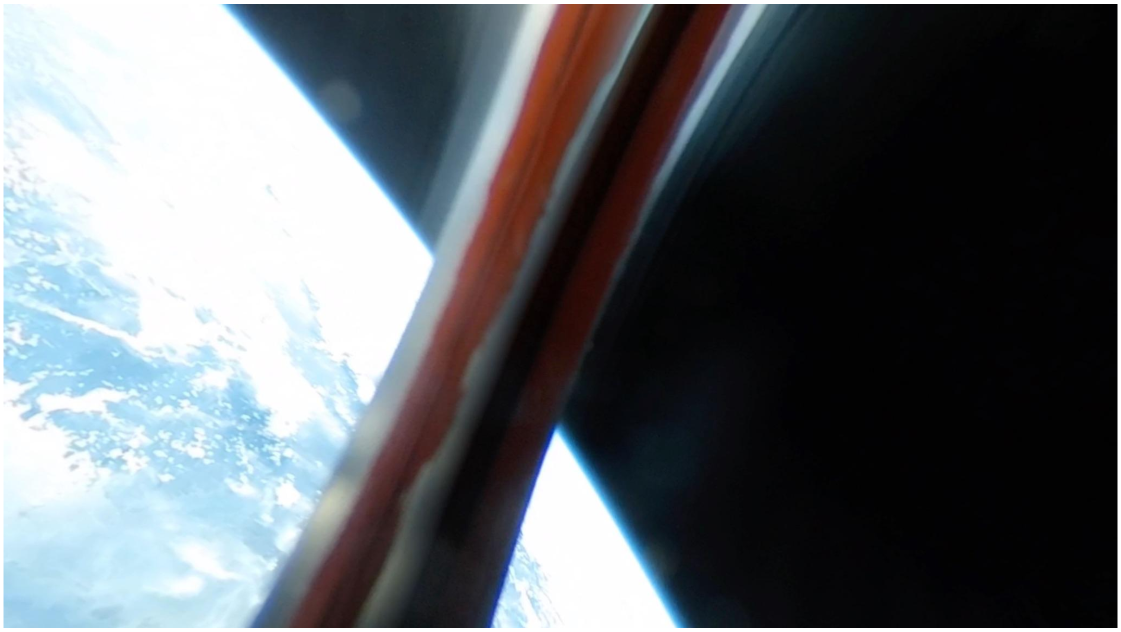


Figure 16: Looking at the horizon in a viewer illustrates continuity

Sensor Data

The payload successfully recorded sensor data from it's boot up on the launchpad until it's shutdown was triggered by TE-2 at T+330s. The sensors were polled and a new set of data points was recorded to the output CSV file every 500 milliseconds. The file name is timestamped with the system date and time accurate to 1 second. The time axis of the CSV file does not have any precision beyond one second which is rounded down meaning that there are two lines with the same time axis value; this is the result of an oversight during the final integration. The time of the launch was approximated within the data by identifying the drastic change in acceleration. Plotting and further analysis of the data lead the CC of CO team to some interesting conclusions.

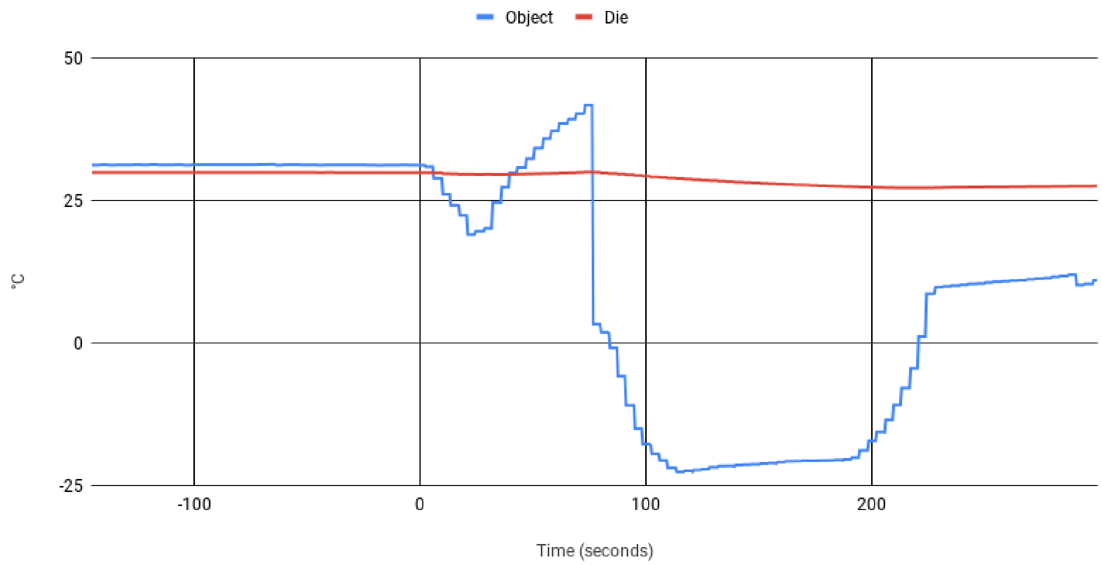


Figure 17: Temperature sensors over time

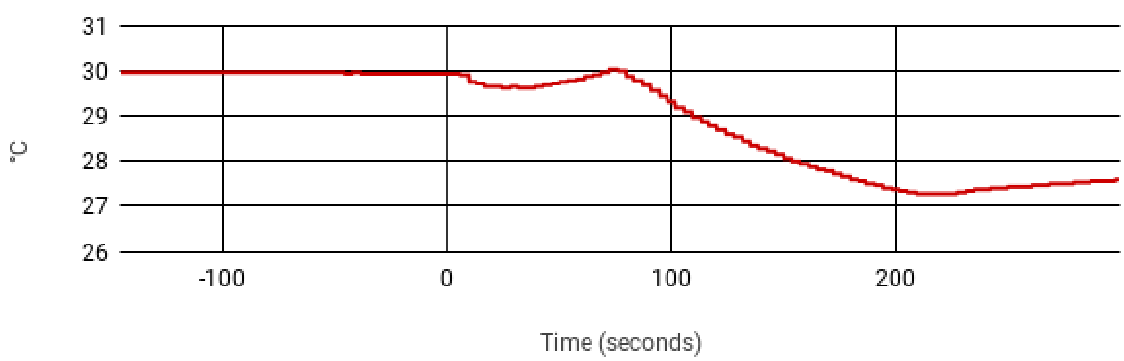


Figure 18: Die temperature over time

The temperature sensor was facing the camera casing, with the object temperature being the temperature of the camera casing measured by the infrared sensor and the die temperature being the temperature of the sensor board itself. The additional valley between the T+85s mark and the T+225s mark coincides with the extension and retraction of the arm. The increase in distance decreased the raw temperature value that was measured. If this additional drop is ignored, a rapid decrease in camera case temperature is observed when the shell is ejected followed by a slow rise of about 7° degrees with what we assume to be heat from the camera running in 4K mode combined with its exposure to sunlight.

The die temperature is measured by a surface-mounted sensor on the temperature sensor's board. This temperature reading did not experience the same drastic changes that the object temperature did but shows similar trends. We believe that the reason why it does not cool down as much is because of the heat created by the sensor's operation because both sensors report a similar temperature prior to launch ruling out a calibration issue.

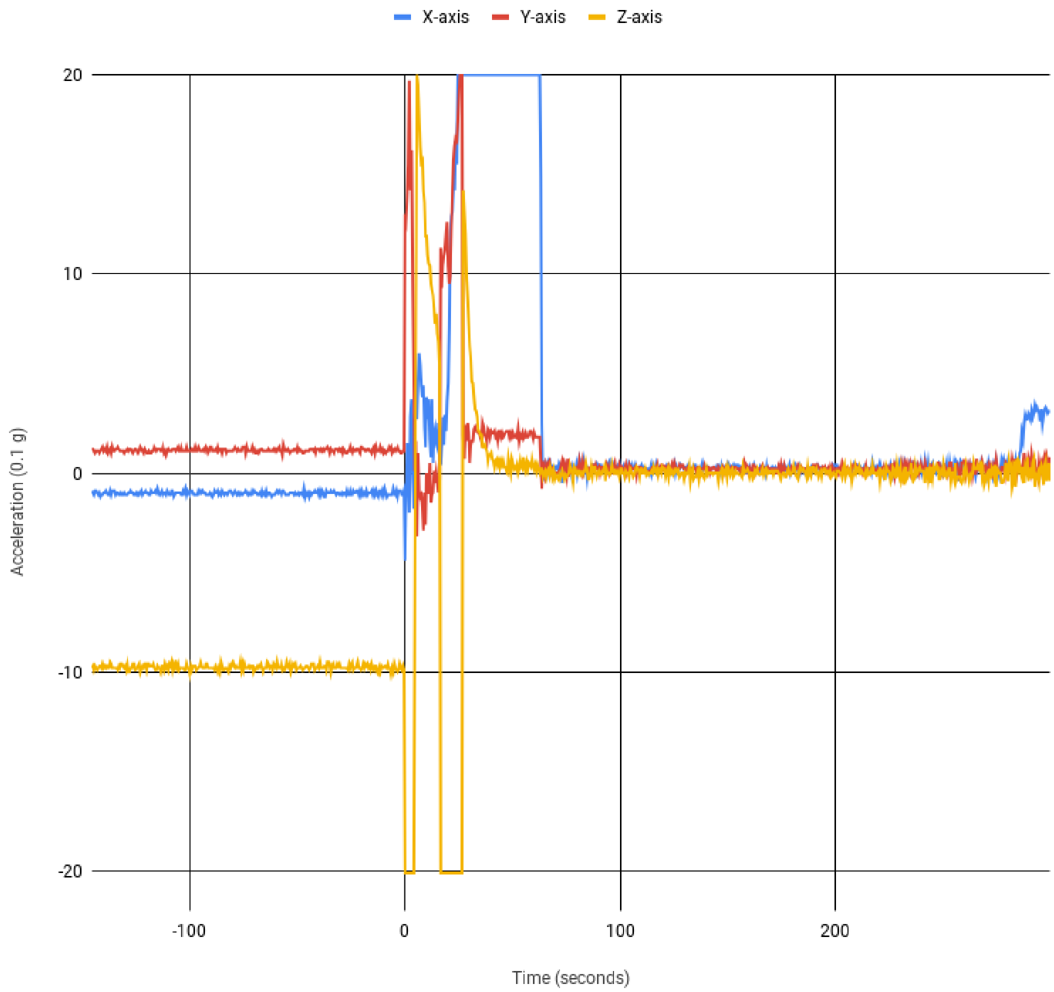


Figure 19: Acceleration sensor

The z-axis of our sensor is the vertical acceleration of our payload, parallel with the direction of the sounding rocket. Sitting on the launch pad there is almost 1g of acceleration on the z-axis downwards: the Earth's gravity. Upon launch the sensor immediately reports it's upper limit of 2g of acceleration upward.

Near the T+5s mark the payload decelerates as the first stage burns out and there is a short delay until the second stage is ignited. Despin can be identified by the increase in the X-axis acceleration around the T+60s mark, which may be inaccurate due to our poor time axis.

Our accelerometer had several different modes configurable in the software, with the default range being a maximum of +/- 2g. We say that our acceleration sensor was out of calibration because we had the option to put the sensor into the +/- 20g mode to better capture the force of the sounding rocket.

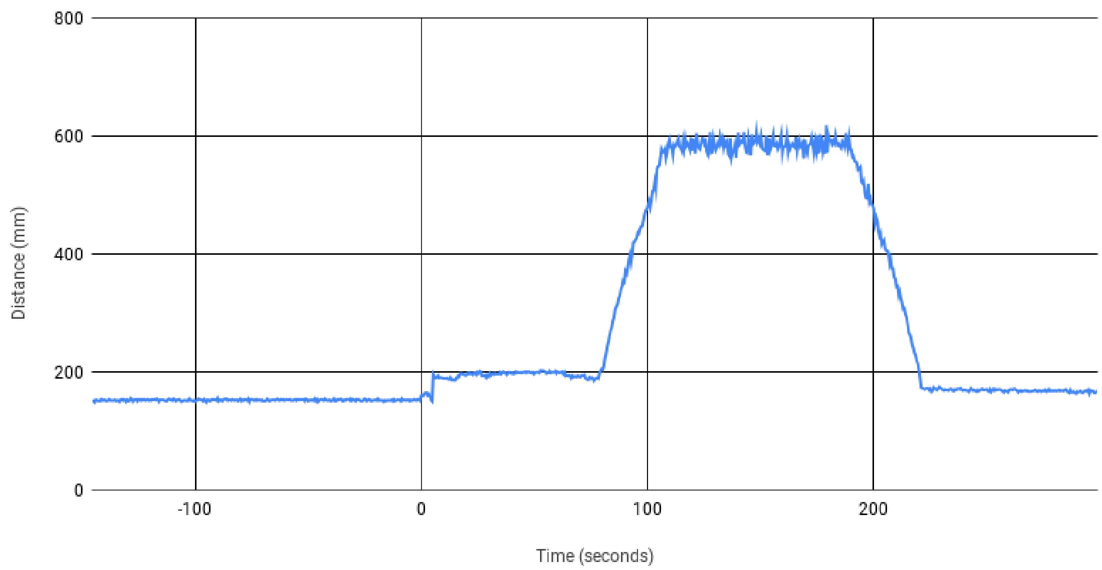


Figure 20: Camera case distance over time

The payload's distance sensor provided valuable insight into the payload arm's movement throughout the flight. The tolerances in the joints of the arm and linear rod extension mechanism required velcro to hold the assembly together for testing. Very soon after launch the distance of the camera case jumps from the fully retracted ~150mm to ~200mm when the centrifugal force created by the spinning of the rocket acts on the arm assembly.

A linear extension and retraction of the arm can be noted. The arm never moves to the fully retracted position it had before the launch, however it is pulled in tighter and closer than it was when it was spinning during launch resting at ~170mm.

The lack of a precise time axis being recorded with every sample due to bad software design prevents an accurate time scale from being recorded with every sensor sample. Although the program waits half a second, millisecond delays in normal computers are usually not accurate and if sampling rate was increased and the system time in milliseconds was added as the time axis the sensor data would be more useful and easier to work with.

Flight Log Analysis

The V.R.S.E. maintains a log of key events and when different tasks begin and end. Every line in the log is time stamped with the amount of seconds relative to GSE power, however the software fails to take into account the 20-25 seconds that it takes the payload to boot up and begin running the control program.

VRSE Flight Log (August 19, 2021)

```
[GSE T+00:00]     V.R.S.E. Payload Control Program Started at system
                time: 2021-06-03 T22:53:28.
[GSE T+00:00]     Operation Mode: MISSION
[GSE T+00:00] GPIO Setup Complete.
[GSE T+00:01] No persisting state was detected, proceeding with normal
                execution order.
[GSE T+00:01] Now listening to timer event signals.
[GSE T+04:02] TE-R signal detected, beginning arm extension and video
                recording.
[GSE T+04:02] Beginning 360 camera recording.
[GSE T+04:02] Beginning arm extension.
[GSE T+04:07]   USB ports have been disabled.
[GSE T+04:14]   Camera has been sent the power on signal via. GPIO.
[GSE T+04:17]   Camera recording has been triggered via. GPIO.
[GSE T+04:17] The 360 degree camera is recording.
[GSE T+04:37] The arm is extended.
[GSE T+04:37] TE-R tasks are complete, waiting for TE-1 signal.
[GSE T+06:02] TE-1 signal detected, retracting arm and transferring low
                quality footage to Pi.
[GSE T+06:02] Beginning arm retraction.
[GSE T+06:12] Waiting for TE-2 signal.
[GSE T+06:16] The 360 degree camera is no longer recording.
[GSE T+06:20] USB ports are now enabled.
[GSE T+06:22] Mounting 360 degree camera SD card over USB.
[GSE T+06:57] All low resolution video files have been copied.
[GSE T+06:58] All buffers have been synchronized with their respective
                block devices.
[GSE T+06:58] Unmounting 360 degree camera.
[GSE T+07:09] The camera is shut down.
[GSE T+08:02] TE-2 signal detected, exiting signal listen mode and
                shutting down electronic systems.
[GSE T+08:02] The arm is retracted.
```

It can be noted that the payload logged the arm as being retracted right when it was being shut down. Distance sensor readings indicate that the arm never retracted. When the arm retraction thread exits, it reports this message regardless because the only way the method exits is when the retraction limit switch is triggered. The motor was trying to retract the arm the last 5 centimeters until it powered down. Due to the design limitation identified with the arm, this was to be expected.

Deviations in Timing and Activation Sequence

In our team's original planning, we intended for the V.R.S.E. payload to record a video that captures the time before, during, and after apogee. After examination of the payload's flight log and comparing the times against when the software logged the detection of the TE-R event, which we assumed to be accurate, we noticed that not only did the payload boot up and begin logging sensor data much sooner than we had expected but that the time between the extension and retraction events was shorter than we had planned: 120 seconds or 2:00 between extension and retraction instead of the 176 seconds or 2:56 between these events.

In our testing during the final integration at RRCC it takes the camera 12 seconds to begin recording after the extension event is received. As mentioned earlier in the payload design section, the 360° camera is programmed to stop recording 10 seconds after the retraction timer event fires and the arm begins retracting. Due to slight variations in the time it takes to disable the USB ports to begin recording as well as the half second required to pulse the record signal to the 360° camera, there is an additional second of play in how long it takes to start and or stop the video.

Our payload recorded a video that is 1:57 long. During sequence testing, the inhibit wire that is cut during RBF procedures prevents any locomotion of the arm but runs all other procedures normally, including the recording and transferring of video footage. When comparing the final flight video to videos recorded in testing, we found that the tests performed in Boulder on June 10, 2021 through those performed at Wallops Flight Facility on June 25, 2021 were 2:53 long with the videos from the final tests on August 13, 2021 being 1:57 long. The delays in the recording starting and stopping explain why the videos are consistently 3 seconds shorter than the time elapsed between TE-R and TE-1.

Both the inspection of the log and recording lengths point to our team's TE-1 timer event having been changed between June 25 and August 13

	Expected		**Logged**	
Signal	**Relative to Launch**	**Relative to TE-R**	**Relative to Launch**	**Relative to TE-R**
GSE-1	T-30s	-30s	T-180s	-265s
TE-R	T+85s	0s	T+85s	0s
TE-1	T+261s	176s	T+205s	120s
TE-2	T+330s	245s	T+330s	245s

Table 6.1: Activation Sequence Specified vs. Observed

Our deduction was confirmed when we obtained a copy of the Mission Timeline document revision G dated July 30, 2021, which shows the timer events for each team after launch. CC of CO arm retraction event (TE-1) was in fact written as T+205s instead of the T+261s we had originally specified in our FMSR.

After reviewing all of our communications we have determined it not to be a miscommunication at the fault of our team; it happened further down the line. The miscommunication happened when our team's liaison confirmed the new timing events in email, but referenced the manifest when updating telemetry channels. The older timer events in the manifest were taken as what was intended rather than the newer ones communicated in email.

Although this change in timing resulted in a 21.4% shorter final video output, further investigation that the change in length prompted proves that the payload software consistently and reliably responds to timer events and that the problem originated externally and is not a result of a fault in the payload design itself.

Signal	**School**	**Start**	**Dwell**	**End**	**Description**
GSE-1	CC of CO	T-30s	Flight	Flight	Power on experiment/Raspberry Pi, begin logging sensor data.
GSE-2	WVSU	T-180s	Flight	Flight	Power on experiment
TE-R	CC of CO	T-30s	245s	330s	Power to motor hat, begin arm extension, begin 360 camera recording
TE-1	CC of CO	T+261s	59s	330s	Begin arm retraction, stop recording 10s after arm retraction begin, transfer low resolution footage to Pi and then shut down 360 camera
TE-2	CC of CO	T+330s	5s	335s	Stop sensor data recording, sync all buffers to storage devices, shutdown Raspberry Pi
TE-3	VWSU	T+321s	Flight	Flight	Latch of experiment internal battery

Table 6.2: Activation Sequence Specified in FMSR (CC of CO & WVSU)

Our sister payload from WVSU used the GSE-2 line for their experiment's power. We confirmed with their team that they received power and began recording sensor data at the correct time.

The premature startup of the payload can be explained by our probable mistake of soldering our GSE-1 line to the GSE-2 pin on the Wallops power interface. This mistake does not negatively affect the data or final results of the experiment, however it does log a lot of useless sensor data at the beginning; there are no meaningful changes in sensor readings when the payload is sitting still on the launchpad.

7.0 Conclusions

In conclusion, our team is confident in saying that the CC of CO RockSat-X 2019-2021 payload was an overall primary mission success. The loss of the 21.4% of video footage is an unfortunate result of miscommunication but was at no point the result of a subsystem failure on our payload. The UHD video footage was successfully recovered from the MadV's SD card. The standard definition footage was successfully transferred from the MadV camera to the Raspberry Pi inside the Ebox. All seals remained intact after reentry and splashdown and ensured that our Ebox was completely dry after recovery. The 360° video footage was successfully stitched together and depicts a wonderful immersive view of the sounding rocket body as well as other projects within view and a beautiful view of the earth. As well as footage of what we believe to be a satellite coming into view over the curvature of the earth near the end of the video. The Scissor Arm system performed as anticipated and there were no visual discrepancies seen during extension or retraction in the collected video footage. The velcro patches held the camera case within the keep out zone successfully during mounting and did not inhibit the camera from extending during apogee. We did not lose a single component during reentry and splash down. Everything that was mounted to the baseplate was still mounted with the exception of our exposed wires for the video data transfer which were incinerated during reentry.

The sensor data we collected was great but not the best. We left the accelerometer sensor calibrated to read data only between -2 and 2 g's of force which resulted in a very limited range of actual reasonable data. The video length also did not reach the calculated length of about 3 minutes but again, that was due to an issue outside of our control.

Overall with mission success, there was still a lot learned individually and as a team. Within the short time frame of 4 months, the 2021 team was able to redesign the CAD and get all parts milled in aluminum. Design, test, and build a working electrical system, and design, test, and implement a working program all of which behaved as it should.

8.0 Potential Follow-on Work

We believe that although our payload was mission successful, that this is just a preliminary step for future work to be conducted. We were contracted to collect video data but what we really did was develop a platform for external rocket body experimentation. Our design would be appropriate to use on future missions testing or collecting data outside of the rocket body where the space is much less limited. Also, this platform still worked with a heavy forward facing load since the payload was in low gravity. In addition, we found that the Madventure 360 camera is relatively easy to use with externally programmed, low-voltage signals and collects high quality video and pictures at a good price point. We also recommend that a different site glass be used, since ours did break on re-entry. We used 3" diameter, 1/16" long ultra-high-temperature quartz glass, but feel that 1/8” may have fared better against impacts. We also recommend using flexible 1/4" tinned copper metal braided sleeving as RFI Shielding to protect exposed wires for data transfer.

If our design is used again in any capacity, we recommend that improvements be made in the CAD, specifically the linear rod points of attachment. However since the Ebox performed well, we recommend it's reuse on the next project. Since we did not have the distal arm members being held by the linear actuator, we had to use velcro to hold the camera in place during integration. This problem would have been alleviated if the linear rod attachment had extended all the way to the most distal arm member. In our design, mounting the linear rod to the most distal arm member was not entirely possible because the range of motion of the linear rod would have hit the longerons at the length that would have been required for full extension.

9.0 Benefits to the Scientific Community

The Ebox Electronics Sleeve was a complete success and we recommend it be implemented in other projects to increase the amount of surface area available for mounting circuits while also increasing structural integrity. The sleeve was 3D printed with a MarkForged Mark II (see Appendix for more information on MarkForged 3D printers) using Onyx filament. Onyx is a micro carbon fiber filled nylon composite that has a heat deflection temperature of 145 °C and a tensile stress at break point of 37 MPa. (see Appendix for Onyx Data sheet) Originally the concept to secure the components in the electronics box was a card that would slide into a track that was milled into the electronics box. This was unfortunately only feasible for additive manufacturing and not subtractive manufacturing. With a sleeve design we were able to ensure that all 4 sides of the Ebox were usable as space to mount our project's electronics and sensors with room to spare. The benefit of 3D printing the sleeve is that it can be as custom as needed for any specific piece of electronics as well as adding any mounting fixtures or holes for cable management and to properly fasten electronics.

We recommend the Mold Max® 60 Higher Heat Resistant Silicone by Smooth On for custom gasket material. It was developed for high-heat resistance applications and will withstand up to 560°F / 294°C. It featured a low mixed viscosity and the cured rubber exhibited very low linear shrinkage. There were two parts A & B which were mixed 100A:3B by weight on a small digital scale and then degassed in a vacuum chamber at 25psi for three minutes. The pot life is 40 minutes which allowed us to scrape the mixture into our aluminum pieces. The gaskets cured in 24 hours to a relatively hard Shore 60A so we could still remove the casing lids. The ebox was completely dry inside after the payload was recovered. The camera was wet, but only because one of the site glasses was broken on re-entry. After careful examination, we postulate that when our plastic wire connectors melted, the tether came loose and may have broken the glass since it's the glass facing the interior of the payload and is somewhat protected during impact.

Additionally, we were surprised at the simple solution of velcro tabs for keeping the scissor arm completely folded during Wallops integration and testing to ensure it would stay within the keep out boundaries on the plate. Those small velcro stickers worked amazingly well at holding the weight of the camera, even if the plate was vertical and the camera pointed down for over 24 hours. And because of the application of the force from the linear actuator, our motor had enough torque to break the velcro at apogee. Unfortunately, as seen in section 6, it was apparent that the velcro was unable to hold the camera in place during launch. Regardless, this was a great way to add some extra security without adding much cost, weight, or additional electronics that could potentially fail. We also recommend the use of a small roller wheel to test arm extensions such as ours. It helps to simulate what the actual conditions will be like at low-gravity without putting additional stresses on the system and also would replace the delrin ramp.

10.0 Lessons Learned

This project had a variety of extremely challenging environmental factors such as a complete team turnover and a global pandemic. The following list is what the 2021 team considered to be key lessons learned from our time on this mission.

- Electronically, we would have triple checked our sensor settings and added a pi camera to film the scissor arm extension and retraction. More data is never a bad thing as long as it doesn't affect your primary mission.
- We should have implemented more robust testing practices so that we have better control sensor data to compare the flight data from.
- The video starting during extension was an improvement from where we originally started, which was to start video recording after arm extension, but if this project was to be done again, starting the video before the shell of the rocket ejects and capturing the full arm extension would be an incredible addition to the footage.
- Measure twice, cut once. On the underarm track that our limit switches were housed in, one of the holes that held the limit switch was 1mm offset from its correct position. We were able to correct the error by adding a glob of JBweld to the lever of the limit switch to ensure that it was depressed at the correct time.
- Always check with your teammates before you make any permanent alterations to any of the equipment. Our team had two sets of aluminum milled arm members and one team member drilled out holes to make a prototype arm to be used in testing. It wasn't until the team chimed in that everyone understood that those arm members might be needed in the future.
- Be honest with your team, your advisors, your mentors and yourself about your capabilities, where the project is and where it needs to be. Everyone is here to help your team succeed, and by being honest, you allow them the opportunity to help you stay the course.
- Ask, Ask, Ask questions! No one will or should judge you for asking a question if you don't know something. This project is a learning experience and you should not be expected to know everything about what you are working on. You have ample resources and asking questions shows that you care about your work not that you are incompitent in your work. Be sure to advocate for yourself in situations where you feel you are not being heard.

- Always plan for everything to take about four times as long as you think it should and start fast-prototyping ASAP. Something we wished we had done was have a little extra time to do some of the more fun and creative testing, like building a cardboard rocket body, or taking our camera on a fourteener and checking video range, etc.
- Don't be afraid of honest discourse between all teammates, and recognize that everyone's behavior and attitude affects other teammates, even if they don't show it. Everyone will have a bad day and everyone will get stressed out, just try to recognize it when it's happening, and give yourself and your teammates a break when it does. If and when disagreements erupt within the team, take a moment and ask if the problem is really something that could affect mission success or if it's a potentially bruised ego speaking up because feelings are hurt.
- When designing your hardware in CAD, understand what is physically millable versus what can be made with a 3D printer. If your parts are going to be milled eventually, design them with that in mind and not what is more efficient for your 3D printer.
- Reach out to local resources outside of RRCC, ACC and CU boulder. Most everyone loves hearing about this project and would love to help. Just make sure you communicate your intent to expand your resources. Our team found a machine shop who would be a viable resource to any future team.
- Dedicate a solid 24 working hours to interpreting, questioning and understanding your user's guide for this project and sit down with your team and make sure everyone is on the same page. There will be plenty of questions down the road while you work on your project that can be answered in your user's guide.
- Do not sacrifice your own personal wellbeing for this project. Take care of yourself first, and that way you have the ability to bring your best to the mission when you can. Know it is okay to require breaks, and ask for reasonable working conditions and stress levels.
- This is a team project. If you find yourself feeling solely responsible for the outcome of the mission, know that something has gone wrong. Don't wait to reach out and get help, and take note that this is not going to be something 1 or even 2 people can accomplish on their own.
- Know that your teammates are their own people with their own thresholds for stress, personal responsibilities etc. Know that working closely with people over an extended period of time in a mission like this can be difficult. Remember to respect the boundaries of others and communicate yours appropriately.
- Assume everything you build has one or more flaws that will come out in testing. Try to anticipate any failure before it happens, and do your best to "break" your prototypes to find weaknesses. This applies to code, mechanical, and electrical systems.
- Timer events should be one of the top priorities from the get-go. Know which signals you are depending on early on and if they require changes, communicate them clearly and repetitively.

- Public chat forums are a great way to communicate after hours and update your team on any individual or overall progress made towards the project. It is also a great tool to hold information to reference for later. This form of communication is open to a lot of interpretation and it is important to remember to speak to someone directly to sort out any misunderstandings. If you do decide to communicate on a form like this, it is a good idea to add your advisors so they can monitor progress as it happens organically.

11.0 Appendices

RockSat-X User's Guide Revision 12
RockSat-X_Users_Guide_Rev_12.pdf (colorado.edu)

MadV - 360° camera
Amazon.com : MADV XiaoMi Madventure 360 Camera, 4K Video, 24MP Photo, Waterproof, Selfie-Stick and Tripod Included : Electronics
Unfortunately the camera and company are no longer in business so the only reference we have for the camera is an Amazon Link.

MarkForged Mark II 3D printer
Carbon Fiber Composite 3D Printer: Markforged Mark Two

Onyx Data Sheet
http://static.markforged.com/downloads/composites-data-sheet.pdf

Smooth On Mold Max® 60 Higher Heat Resistant Silicone
(technical and material data sheets)
https://www.smooth-on.com/products/mold-max-60/

Shore Hardness Scale
Durometer Shore Hardness Scale (smooth-on.com)

Rust-Oleum High Heat BBQ Spray Paint
https://www.homedepot.com/p/Rust-Oleum-Specialty-12-oz-High-Heat-Satin-Bar-B-Que-Black-Spray-Paint-7778830/202315061

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